Research papers

Effects of check dams on runoff characteristics along gully reaches, the case of Northern Ethiopia

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A B S T R A C T

In the Highlands of Northern Ethiopia soil and water conservation (SWC) practices, including construction of check dams in gullies, have been widely implemented for the last three decades. Despite this extensive installation of check dams, their effects on runoff response are not well understood as compared to those of other SWC practices. Hence, this study examines the effects of check dams on runoff response in gully channels. 90 degree V-notch weirs were installed to measure a wide range of runoff discharges at the upper and lower sections of five gully reaches: two channel cut in sandstone (a gully with check dams and vegetation (SCV) and an untreated gully (S)) and three cut in limestone (an untreated gully (L), a gully with check dams but no vegetation (LC) and a gully with check dams and vegetation (LCV)). Automatic sensors were installed to monitor runoff depth during two rainy seasons (29/08/14 – 17/09/14 and 24/7/15 – 14/09/15). All runoff characteristics at the lower section of each gully reaches were calculated for a gully reaches length of 50 m. In the sandstone area, the results show longer lag times of runoff to reach the lower section of the channel reach in the treated gully (SCV) compared to the untreated gully: difference in time lag to production of runoff equals 51% for runoff initiation, 61% for peak runoff and 44% for runoff end. An increase of hydraulic roughness by check dams and water transmission losses in deposited sediments are responsible for the delay of runoff to reach the lower part of the gully channels. In the limestone area, different time lags were recorded in different gully reaches regardless of the treatment effects (lag to runoff initiation, lag to peak flow and lag to runoff end were larger at LC, L and LCV, respectively). The reduction of peak runoff discharge between the upper and lower gully sections was larger in the gullies with check dam and vegetation (8–17%) than in gullies without treatment (5–6%). Reduction of runoff volume between these 2 gully sections was also larger in treated gullies than in untreated gullies: i.e. 18%, 9% and 8% in SCV, LCV and LC, respectively while it was only 4% in S and 6% in L. This study shows that the implementation of check dams combined with vegetation reduced peak flow discharge and runoff volume as large sections of runoff infiltrated in the sediments deposited behind the check dams. As gully check dams are implemented in a large areas of the North Ethiopia Highlands, this contributes to groundwater recharge and increased river base flow.

1. Introduction

Soil and water conservation (SWC) practices affect the water balance of a catchment by altering the major hydrological components. Hillslope runoff, base flow and stream flow are influenced through the implementation of different SWC practices e.g. terraces, check dams, afforestation (Haregeweyn et al., 2015; Huang and Zhang, 2004; Zhang et al., 2014). In the Tigray region of northern Ethiopia, extensive SWC structures have been installed during the last three decades. Dry masonry stone bunds on hillslopes and check dams in gullies resulted in enhanced infiltration and spring discharge and reduced soil erosion rates (Nyssen et al., 2010; Nyssen et al., 2008a,b) while gullies are stabilized following check dam construction (Frankl et al., 2013). A significant decrease of runoff production was reported after installing exclosures on degraded land (Descheemaeker et al., 2006) and implementation of stone bunds with trenches on cultivated land and rangeland (Taye et al., 2013).

A check dam is a structure constructed of stone or other material placed across the flow channel to be used as a barrier for soil and water losses. It is a common SWC technique used in areas
where gully development is a problem (Frankl et al., 2011, 2013; Huang et al., 2012; Nyssen et al., 2004). It is widely implemented in China (Xiang-zhou et al., 2004), Ethiopia (Nyssen et al., 2004), Italy (Bombino et al., 2009; Lenzi and Comiti, 2003), US (Diaz-Ramirez, 2014), Spain (Romero-Diaz et al., 2007) and Iran (Hassani et al., 2009).

Several studies indicated the effectiveness of check dams in slowing down water and sediment movement along gully and stream channels (e.g. Castillo et al., 2007; Hassanli et al., 2009; Nyssen et al., 2004; Polyakov et al., 2014; Remaître et al., 2008; Xiang-zhou et al., 2004; Xu et al., 2013). Nyssen et al. (2010) evaluated the impact of check dam constructed in degraded catchments on runoff abstraction and concluded that this intervention resulted in the rise of the ground water table, emergence and expansion of cropped fields in stabilized gullies and prolonged crop-growing periods. Despite its extensive practices and environmental importance, particularly in arid and semi-arid regions, its effects on runoff characteristics are poorly understood in Ethiopia as compared to other SWC techniques such as exclosures or stone bunds (Descheemaeker et al., 2006; Nyssen et al., 2010; Taye et al., 2013; Vancampenhout et al., 2006). In north Ethiopia where check dams are widely implemented as a SWC technique to control gully erosion (Nyssen et al., 2004), the extent to which it affects hydrological processes such as on peak flow discharge, lag time, runoff volume and infiltration has not been quantified. The runoff responses in gullies to check dam construction depend on lithology and vegetation characteristics in the gully. Check dams may also impact the transfer of runoff from uplands to lower areas and hence also the runoff connectivity in the landscape. We hypothesise that check dams have a significant effect on runoff characteristics in gullies. To evaluate the impact of check dam construction in gullies on runoff, it is important to compare the runoff response of gullies with without and check dams. The objectives of this study are to quantify the time delay of runoff at lower sections of gully reaches due to check dam construction in different lithologies and to quantify the peak flow and runoff volume reduction due to check dams constructed in gully reaches.

2. Materials and methods

2.1. Study area

The study area (Fig. 1) is located in the Dogu’a Tembien district (Hagere Selam), in Tigray region, north Ethiopian highlands, ca. 45 km west of Mekelle, capital of the region. Geographically it is located at 13°40’ N, 39°14’ E at elevations around 2430 m a.s.l. Specifically, five gully reaches, without tributaries, were chosen as experimental sites in order to represent the two dominant lithologies of the study area (Figs. 1 and 2). Two gully reaches in sandstone selected: One gully with check dams and vegetation (SCV) and one untreated gully (S). Three gully reaches in limestone were chosen: an untreated gully (L), a gully with check dams but without vegetation (LC) in channel bed and a gully with check dams and vegetation (LCV) (Table 1). The study area was selected as it is one of the more degraded areas in the region but extensive SWC measures have also been taken including check dam construction for gully erosion control.

The study area is characterized by a short but intense rainy season restricted to mid-July to early September (Nyssen et al., 2005). Annual average precipitation ranges from 550 to 900 mm (Gebresamuel et al., 2010; Nyssen et al., 2005; Taye et al., 2013). The precipitation is also characterized by intense showering (Virgo and Munro, 1978) and large drop sizes (Nyssen et al., 2005). Considerable interannual variability of rainfall and severe soil moisture deficit characterize the region. The average monthly air temperature varies between 12 and 19 °C.

The soils of the study area are young due to active erosion and deposition process (HTS, 1976; Nyssen et al., 2008b; Van de Wauw et al., 2008). At the studied gully sites on sandstone and limestone Cambisols and Regosols dominate (Van de Wauw et al., 2008). The channel bed and walls (especially at the lower part) of S gully are very stony and show very little soil profile development while gully channels with check dams are filled with 1–2 m thick coarse sediments, resulted in sandstone alluvio-colluvial fill in SCV and mixture of limestone and sandstone fill in LCV and LC. Both sides (walls) of the channel of treated gullies with check dams are characterized by shrub and grass vegetation. However the vegetation in the LC gully channel bed was completely cleared in order to contrast it with the vegetated LCV gully.

The livelihood of the people of the study area is mainly agriculture, hence land use is dominated by cropland followed by grazing land, bush land and bare land (Gebresamuel et al., 2010; Taye et al., 2013). Rangelands mainly found on steep slopes are overgrazed by livestock so that these lands have a low vegetation cover. The study area has lost its native forests long time ago (Gebru et al., 2009; Nyssen et al., 2004) and the remnant patches of forests are usually limited to inaccessible areas and around churches (Gebru et al., 2009; HTS, 1976; Munro et al., 2008). Land use patterns have resulted in severe soil erosion and gully formation in the area (e.g. Frankl et al., 2011, 2013; Munro et al., 2008; Nyssen et al., 2004). Over the last three decades extensive land management activities have been made to reverse the environmental degradation (Descheemaeker et al., 2006; Munro et al., 2008; Nyssen et al., 2004; Taye et al., 2013). The establishment of stone bunds on farmland (Nyssen et al., 2008b; Taye et al., 2013; Vancampenhout et al., 2006) and the construction of check dams in gullies (Frankl et al., 2011, 2013; Nyssen et al., 2004) have resulted in significant effects on environmental restoration. At present, forests are re-appearing following rehabilitation of marginal lands or exclosures (areas set aside for restoration of vegetation) activity implemented in the region (Aerts et al., 2006; Descheemaeker et al., 2006; Munro et al., 2008).

2.2. Methodology

2.2.1. Installation of measuring set up

In open stream, runoff discharge increases at the lower section of the stream as it receives more runoff from upland areas than the upper section (Easton et al., 2010; Tebebu et al., 2010). In the present study, all lateral inflow between the upper and lower sections were diverted to quantify the effects of check dams on runoff in gullies. Diversion canals were constructed on both sides of the gullies so that external inflow runoff could not enter the targeted gully reaches (Fig. 3). The diversions were put in carefully to avoid the development of new gullies. The average channel slope gradient between the two gully sections ranged from 4.6% to 5.8% (Table 1).

Disturbed and undisturbed samples were collected from each gully bed, between the upper and lower V-notches to determine organic matter content, dry bulk density and texture. Two composite sediment samples (one closer to the upper section and the other closer to the lower section) from each gully reach were taken from 50 cm deep pits and two core samples of undisturbed channel bed material were taken to determine organic matter content. Characteristics of the gully reaches at the study sites are summarized in Table 1. To monitor runoff, 90° V-notched weirs (Bos, 1989; Hudson, 1993) were installed at the upper and lower sections of gully reaches (Fig. 4). The V-notch weir, also called triangular weir, has an overflow edge in the form of an isosceles triangle necessary to
measure a wide range of flow discharge (low to high flow) (Bos, 1989; Hudson, 1993). The study sites are characterized by high runoff and sediment transport (Haregeweyn et al., 2005). As fully or partially contracted V-notch (Bos, 1989; Hudson, 1993) is sensitive to sedimentation the modified 90-degree triangular V-notch (van den Elsen et al., 2003) was adopted. This modified V-notch has 2 cm height below the V-notch opening, 100 cm height opening and 2 m length across the flow channel. The wall of the V-notch (50 cm thick and 50 cm foundation) was constructed with stone and cement to avoid the risk of collapse. Canals were constructed between the upper and lower gully sections to divert side external inflow (Fig. 3) and construction of side walls was also necessary to control bypass of water (Fig. 4).

Monitoring of runoff depth was done by installing e+ WATER 100L sensors (Fig. 4) which combine a data logger at the base to measure the water pressure and atmospheric pressure sensor above the water surface. This sensor measures a 0–100 cm water column with 5 mm accuracy and 1 mm resolution. The runoff measurements were done from 29 August – 17 September in 2014 and from 24 July – 14 September in 2015.

Automatic and manual rain gages were installed at three locations: Adikolakul close to S and SCV, Adigoshu station nearby LCV and LC and Alassa station close to L gully (Fig. 1).

2.2.2. Runoff discharge equation

Several equations for flow discharge calculation are available from the flow depth produced by 90-degree V-notch weirs (Bos, 1989; Hudson, 1993). As the V-notch used for the present study is modified in order to fit the local conditions, high runoff and sediment transport, the modified discharge calculation equation (van den Elsen et al., 2003) is adopted to describe the runoff depth as open channel rate (Q):

$$Q = C \left( \frac{g}{2} \right)^{h_c} \tan \left( \frac{\theta}{2} \right)$$

where $Q$ = discharge (m$^3$/s); $C$ = correction factor; $g$ = 9.8 (m/s$^2$); $h_c$ = depth of flow (m) and $\theta$ = angle of V-notch (in $^\circ$).

C combines $C_d$ and $C_v$ coefficients. $C_d$ is a correction factor, also called discharge coefficient, to be applied to correct for effects such as viscosity, turbulence and a non-uniform flow distribution (Bos, 1989). Applying this correction factor is important as high suspended sediment concentrations in the study area cause higher flow viscosity. While it is also affected by the type of weir the coefficient $C_d$ ranges from 0.93 to 1.02 (Bos, 1989). $C_v$ is a correction factor for water velocity upstream of the V-notch. In line with earlier studies (van den Elsen et al., 2003), 0.9 is assumed as correction.
factor (C) and the value was also checked as it is accurate by comparing discharge obtained by the equation and discharge from direct measurement of velocity multiplied by cross-sectional area of the stream (van den Elsen et al., 2003).

The discharges obtained from Eq. (1) were used to calculate the total runoff event volume.

2.3. Data analysis

The hydrographs were constructed for each runoff event at the upper and lower cross-sections of all gully reaches. Different lag times (lag to initiation, lag to peak and lag to end) of runoff to reach the lower V-notches were computed and compared among gully reaches. The proportion of average difference between upper and lower peak discharges, flow time and runoff volume are important parameters to compare the effects of gully characteristics on runoff. Simple linear regressions were performed to correlate event peak flow discharges to event maximum rainfall depth per 5 min, peak flow discharge reduction to maximum event rainfall depth and intensity, event volume of runoff to rainfall to draw conclusions on the relationship between rainfall parameters and runoff in gully conditions. With the assumption of linear relationship

Table 1

<table>
<thead>
<tr>
<th>Gully reach</th>
<th>Number of check dams</th>
<th>Vegetation cover in the channel</th>
<th>Channel width (m)</th>
<th>Gully reach length (m)</th>
<th>Channel area (m²)</th>
<th>Gully reach area (m²)</th>
<th>Average channel slope gradient (m m⁻¹)</th>
<th>Check dam age (year)</th>
<th>Channel bed material/sediment</th>
<th>Organic matter content (%)</th>
<th>Texture</th>
<th>Bulk density (g cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>0</td>
<td>0</td>
<td>2.28</td>
<td>78</td>
<td>178</td>
<td>618</td>
<td>0.046</td>
<td>NA</td>
<td>0.14</td>
<td>Sandy clay</td>
<td>1.62</td>
<td></td>
</tr>
<tr>
<td>SCV</td>
<td>7</td>
<td>40%</td>
<td>3.63</td>
<td>95</td>
<td>345</td>
<td>1248</td>
<td>0.048</td>
<td>14</td>
<td>1.54</td>
<td>Sandy clay loam</td>
<td>1.49</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>0</td>
<td>0</td>
<td>1.45</td>
<td>56</td>
<td>81</td>
<td>364</td>
<td>0.058</td>
<td>NA</td>
<td>2.06</td>
<td>Clay</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>LC</td>
<td>4</td>
<td>0</td>
<td>1.54</td>
<td>66</td>
<td>102</td>
<td>757</td>
<td>0.055</td>
<td>7</td>
<td>1.56</td>
<td>Sandy clay loam</td>
<td>1.61</td>
<td></td>
</tr>
<tr>
<td>LCV</td>
<td>7</td>
<td>35%</td>
<td>3.36</td>
<td>80</td>
<td>269</td>
<td>1268</td>
<td>0.051</td>
<td>7</td>
<td>1.8</td>
<td>Sandy clay loam</td>
<td>1.56</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Selected gully reaches with and without check dams and vegetation along the channels. For information on S, SCV, L, LC and LCV see Fig. 1.

Fig. 3. Schematic representation of V-notch installation at the upper and lower section of gully reach. The gully length is not at scale for sake of clarity.
between runoff characteristics and distance between the upper and lower sections of the gullies, all runoff values at the lower section of all gully reaches are linearly standardized to a length of 50 m of gully reach for analysis. This standardization helps to offset the differences in gully lengths and facilitate meaningful comparison and interpretation of the results in different gully reaches. The length of 50 m was chosen for normalization based on the length of the smallest gully reach (L = 56 m) and with the intention of having the highest and roughly equal number of check dams for the treated gullies, hence 3 check dams in L and 4 in both LCV & SCV after standardization. The higher number of check dams is to adequately differentiate treated gullies from untreated gullies whereas equal number of check dams is to cancel variation due to differences in the number of check dams. The non-parametric Kruskal–Wallis test was used to check if lag times, reduction of peak flow discharges and reduction of runoff volume in gully reaches are significantly different. Student’s t-test was used to check if lag times, reduction of peak flow discharges and reduction of runoff volume within gully reaches and also to compare mean differences in lag times, peak flow discharge and runoff volume. The hydrographs allow to compare the time elapsed for runoff to reach the lower station with reference to the upper station. The hydrographs show variable lag time to runoff initiation, lag to peak and lag to end of runoff between the inlet and outlet of the gully reaches. Gullies with check dams and vegetation show larger differences in lag times between the upper and lower sections of the gullies (Fig. 7). The runoff hydrographs also show that the time of the rising limbs are very short while falling limbs are longer in untreated gully.

Differences in the peak flow discharge were also observed from each hydrographs (Table A.1). Among the whole set of hydrographs the lowest reduction of peak flow discharge between the upper and lower sections was 0.7% at S while the highest loss of peak flow discharge was recorded at SCV (52.2%).

3. Results

3.1. Rainfall

Daily rainfall data is available for three stations (Fig. 5). The total rainfall depths recorded from 29 August – 17 September in 2014 and from 24 July – 14 September in 2015 at Adikolakul station (SCV and S), at Adigoshu station (LCV and LC) and at Alaissa station (L) are 393.6, 348.4 and 272.3 mm, respectively. Event rainfall intensity and maximum rainfall depth per 5 min data are available over the measurement period for Adikolakul station while for the other two stations the data are available only in the second year. All daily rainfall depths over the monitoring period (in 2014 and 2015) and the rainfall depth that correspond to the individual runoff events considered for analyse are indicated in Fig. 5. Most storms with less than 5 mm did not create runoff. Some runoff data were cancelled from further analysis due to inflow of side runoff following accidental collapses of the runoff diversion canal or due to blocking of sensors by sediments. Fig. 6 shows rainfall characteristics at the study sites, all are means over the monitoring period. The mean and duration of storm are larger in LCV and smaller in L while the intensity and peak are larger in Adikolakul and smaller at L.

3.2. Runoff hydrographs at upper and lower section of gully reaches

Runoff hydrographs were produced at the upper and lower section of all gully reaches (Table A.1). The results showed that all hydrographs at the upper and lower stations within each gully have the same shape but are different in time, peak discharge and runoff volume. The hydrographs allow to compare the time elapsed for runoff to reach the lower station with reference to the upper station. The hydrographs show variable lag time to runoff initiation, lag to peak and lag to end of runoff between the inlet and outlet of the gully reaches. Gullies with check dams and vegetation show larger differences in lag times between the upper and lower sections of the gullies (Fig. 7). The runoff hydrographs also show that the time of the rising limbs are very short while falling limbs are longer in untreated gully.

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3.3. Lag time

Lag time, is defined as is the delay time of runoff to occur at lower section of gully reach at the initiation, peak and end of runoff. These lag times are useful runoff characteristics to evaluate the effects of check dams on the delay of runoff along gully reaches. Comparison of lag to runoff initiation at the lower gully reach section shows that runoff was delayed by, 3.59 (±3.64) min, in L followed by SCV, while the lowest mean lag time (1.69 ± 1.26 min) was recorded at S (Table 2). In SCV the time to runoff initiation at lower section is significantly different as compared to the lag time in S and LC. Neither lithology nor the interaction effect of treatment and lithology was found significant on the lag time of runoff initiation.

Testing for the differences in lag time to peak flow discharge at the lower section of the gully reaches showed that the lag time to peak discharge was significantly delayed in SCV (3.07 ± 2.57 min) as compared to all gullies in limestone and sandstone lithologies, but for the other treatments this lag time was not significantly different (Table 2). Considering individual runoff events, the lag time to peak flow discharge ranges from 0.24 min at L gully reach to 9.26 min at SCV gully reach.

The time differences that the flows ceased at the upper and lower sections were also computed and comparisons made between the five gully reaches. The results showed that the lag
time to stop runoff ranges from 0.04 at LC to 18.27 min at SCV. Kruskal–Wallis test indicated that the installation of check dams combined with vegetation in gullies has a significant effect on increasing the time elapsed by runoff to stop at the lower sections of gullies. Pairwise mean comparison revealed that lag time to cease runoff at lower section of gully reaches were significantly higher in SCV (8.83 ± 4.16 min) and LCV (9.59 ± 2.75 min) than in S (4.98 ± 2.88 min) (Table 2). Moreover, the lag time in LCV was significantly greater than in LC and L within limestone lithology. But the results showed that the effect of check dam is independent of lithology and therefore lag times are not affected by lithology differences.

### 3.4. Peak flow discharge

Event peak flow discharges were correlated to event maximum rainfall depth per 5 min (Fig. 8a) and the relation shows a strong exponential relationship for both upper and lower sites (R = 55%). Tests were carried out to check whether there are significant differences in peak flow discharges between the upper and lower gully reach sections. The test did not show any significant differences in all gully reaches. The average peak flow discharges at upper and lower sections of each gully reach were computed over the measurement period to analyse the decrease of peak flows along gully reaches (Table 3). As external inflowing runoff was diverted and the rainfall on the gully itself was considered negligible, one may expect the peak flow discharge at the upper section to be larger than at the lower section of gully reach.

The relative reduction of peak flow discharge at the lower section of the gullies was calculated as (Eq. (2)):

\[
\% \text{ reduction in peak discharge} = \frac{\Delta Q_p}{Q_{pu}} \times 100
\]

where \( \Delta Q_p \) is the difference between upper peak flow discharge (\( Q_{pu} \)) and lower peak flow discharge (\( Q_{pl} \)).

The reductions of peak flow discharges between the upper and lower sections were stronger in the gullies with check dams (8–17%) than in gullies without check dams (5–6%) (Table 3).

The non-parametric Kruskal–Wallis test showed important differences in the reduction of peak flow discharge between gully reaches. Gullies with treatments (check dams, vegetation) have significantly reduced peak flow discharges relative to untreated gullies with the highest reduction reaching 52.2% at SCV gully (Table 3). Treated gullies do not vary significantly from each other as was also found between untreated gullies. Within each gully reach, peak flow reduction is correlated to event rainfall depth and intensity in which inverse relationships were found, however coefficients of determination are small in both curves (Fig. 8b and c).
3.5. Runoff volume

The relationships between event rainfall and runoff volume were analyzed at all sites by simple linear regression (Table 4). Positive and significant linear relations were observed between event runoff volume and rainfall for the upper and lower sections of all gully reaches except in L gully. The dependence of runoff volume on rainfall, especially where significant relations were observed, is illustrated in Fig. 7.

Table 2

<table>
<thead>
<tr>
<th>Gully reach</th>
<th>Lag time (min)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initiation of runoff</td>
<td>Peak runoff</td>
<td>End of runoff</td>
<td>n</td>
</tr>
<tr>
<td>-------------</td>
<td>------------------</td>
<td>-----------</td>
<td>-----------</td>
<td>---------</td>
</tr>
<tr>
<td>S</td>
<td>1.69 a (±1.26)</td>
<td>1.20 a (±0.82)</td>
<td>4.98 a (±2.88)</td>
<td>17</td>
</tr>
<tr>
<td>SCV</td>
<td>3.46 b (±2.43)</td>
<td>3.07 b (±2.57)</td>
<td>8.83 ab (±4.16)</td>
<td>17</td>
</tr>
<tr>
<td>L</td>
<td>3.59 ab (±3.64)</td>
<td>1.92 a (±1.98)</td>
<td>6.19 a (±2.97)</td>
<td>15</td>
</tr>
<tr>
<td>LC</td>
<td>1.77 a (±1.83)</td>
<td>1.29 a (±0.69)</td>
<td>6.73 ab (±3.58)</td>
<td>15</td>
</tr>
<tr>
<td>LCV</td>
<td>2.10 ab (±1.39)</td>
<td>1.24 a (±0.79)</td>
<td>9.59 c (±2.75)</td>
<td>12</td>
</tr>
</tbody>
</table>

Average lag times within a column which have no common letter are significantly different at significance level 0.05.

Fig. 8. Relationships between (a) peak flow discharge – maximum rainfall depth per 5 min at upper section (Upper) and lower section (Lower) of gully reaches; (b) peak flow discharge reduction – maximum rainfall depth per 5 min; and (c) peak flow discharge reduction – rainfall intensity over all gully reaches. Data points in all curves are event based over the five gully reaches.
observed, ranges from 63% at LC to 89% at L gully (Table 4). Hence, in our study area, with typically short but intense storms, rainfall is an important explanatory factor for prediction of runoff volume in gullies with different characteristics.

The relative reduction of runoff volume between the upper and lower sections of gully reaches was calculated as (Eq. (3)): 

\[
\text{% reduction in volume} = \frac{\Delta V}{V_{\text{upper}}} \times 100
\]  

(3)

where \(\Delta V\) is the runoff volume difference between the upper \((V_{\text{upper}})\) and lower \((V_{\text{lower}})\) section of the gullies.

The results showed greater volume of discharge at upper section than the lower section of gullies, but no significant differences were found within each gully. Across lithologies, event volume reductions show a wide range of decrease of discharge volume, 0.4% at S to 52% reduction at SCV. Differences in the fall of runoff volume at lower section of gully reaches across lithologies were tested for their significance by using non-parametric Kruskal-Wallis test. The result revealed SCV significantly reduced runoff volume as compared to gullies without any treatment, S and L (Table 3). Significantly less reduction was also found at S when compared to LC and LCV (Table 3). Significantly less reduction was also found at S when compared to LC and LCV. Gullies with similar characteristics do not have important variations when compared with each another. The reductions are correlated to different rainfall characteristics but no important relation was observed. Fig. 9 shows the total volume of discharges and total reduction in cubic meter and total rainfall during the entire measurement period at each site. During this period (n = 52 runoff events) the total volume of discharges reduced in all gullies was 1325 m³ out of which 66% was at gullies under treatment with check dam and vegetation.

### Table 4

Event rainfall – storm runoff volume relation; with indication of \(R^2\) of the regression function described by slope and significance level (0.05). Upper = upper gully section, Lower = lower gully section. For information on S, SCV, L, LC and LCV see Fig. 1.

<table>
<thead>
<tr>
<th>Site</th>
<th>Station</th>
<th>Slope</th>
<th>(R^2)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Upper</td>
<td>69.2</td>
<td>89'</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>68</td>
<td>88'</td>
<td>17</td>
</tr>
<tr>
<td>SCV</td>
<td>Upper</td>
<td>22</td>
<td>73'</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>20.9</td>
<td>72'</td>
<td>17</td>
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<tr>
<td>L</td>
<td>Upper</td>
<td>10.6</td>
<td>29</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>10.1</td>
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<tr>
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<td>Upper</td>
<td>3.7</td>
<td>64'</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
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<td>63'</td>
<td>15</td>
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<tr>
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<td>Upper</td>
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</tr>
<tr>
<td></td>
<td>Lower</td>
<td>24.6</td>
<td>64</td>
<td>15</td>
</tr>
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</table>

* Indicates significant relationship between daily rainfall and storm runoff volume.

### 4. Discussion

#### 4.1. Runoff hydrographs for different gullies

Adjusting the water depth sensor to fine measuring intervals (one min), provided reliable data particularly for short duration flows that occurred in this study (about 50% of runoff events lasted only for less than 1 h). Hydrographs were constructed for each runoff event which allowed to analyse the runoff response to different gully conditions (Table A.1). Hence, by analyzing the shape of the hydrographs one can observe the differences between runoff hydrographs (lag time, duration, peak and volume) at the upper and lower sections of each gully reach and between different gullies. Significant differences in lag time, decrease in peak flow discharge and runoff volume were not detected between sandstone and limestone lithologies.

#### 4.2. Lag to begin runoff at lower section of gully reach

The results of this study reveal that there is a delay in runoff initiation at the lower section of all gullies during every runoff event. It is not surprising to observe the delay of discharges between the upper and lower sections of gully reaches, as the source of runoff at the lower is only via the upper V-notch. The result to be analyzed are the duration of delay of runoff to reach the lower section of the gully reaches. The longer delay at SCV (3.46 ± 2.43 min) as compared to S (1.69 ± 1.26 min) (Table 2) could be associated to the presence of check dams, sediment deposition, vegetation and low lithology...
bulk density in the former gully channel (Table 1, Fig. 10). Surface roughness, resulting from check dams and vegetation, claimed to slowdown runoff by increasing time of concentration and infiltration (e.g. Deasy et al., 2014; Helming et al., 1998). It was reported that soil bulk density is positively correlated with runoff production (e.g. Calvo-Cases et al., 2003; Descheemaeker et al., 2006), thus affecting runoff discharge and velocity positively. Despite the presence of check dams and vegetation in LCV and check dams in LC the delay of runoff to reach lower section of the gully reaches were shorter than in the L gully which lacks check dams and vegetation (Table 2). This may be explained by the higher rainfall intensities in the LCV and LC that leads to rapid soil saturation and increases the velocity of surface runoff (Brouwer et al., 1985). When rainfall intensity is the same for gullies with and without check dams and vegetation in the same lithology the check dams and vegetation increase lag to runoff initiation at lower section of the gully reach (Fig. 7). The negative correlation between rainfall intensity and lag time (Fig. 11) indicates that the smaller the intensity the longer the lag time of runoff to reach the lower gully sections. Besides rainfall intensity, smaller bed material bulk density (Table 1 and Fig. 10) (Li et al., 2009) and dry conditions of the clay soil (Bouma and Dekker, 1978; Römkens and Prasad, 2006) in L may be hold responsible for the longer delay of runoff by increasing initial infiltration rate.

4.3. Lag time to peak runoff at lower section

In the gully with check dams and vegetation cover in the sandstone lithology (SCV), runoff takes 2.6 times longer to peak as compared to the one without treatment (Table 2). This is related to the presence of check dams, vegetation and sediment accumulation which reduce the runoff speed by increasing channel bed roughness, as described by several authors (Amare et al., 2014; Borst and De Haas, 2006; Deasy et al., 2014; Descheemaeker et al., 2006; Hood et al., 2007; Namadi et al., 2014). In limestone lithology, the longer lag times to peak were recorded in the gully without management intervention (Table 2). This can be attributed to the small rainfall depth (Figs. 5, 6 and 9), clay texture and low bulk density of bed material at L (Table 1 and Fig. 9) gully reach which contribute to an increase of infiltration mainly at the beginning of rainfall (Bouma and Dekker, 1978; Li et al., 2009; Römkens and Prasad, 2006) thereby delaying the time to peak flow at the lower section of the gully reach. Cracking of soil was also noticed in the L gully reach without management interventions, which can also increase infiltration rate particularly at the beginning of runoff generation.

4.4. Lag time to end runoff at lower section

During some rain events termination of runoff discharge was found to be faster at the lower section than at the upper section of gully reaches that can be explained by low rainfall intensity, short rainfall duration and dry soil conditions. Polyakov et al. (2014) reported that after installation of soil and water conservation structures, small rainfall failed to produce runoff that reached the watershed outlet. The authors added that check dams are more likely to reduce hydrologic connectivity between uplands, channel network and outlet during small runoff events than during large runoff events. On average, the time of interruption of runoff discharges was delayed at the lower section of all gully reaches which can be attributed to the temporary storage of water in the channel bed between the two sections. The longer flow time at lower sections is larger in gullies with check dam and vegetation cover (Table 2), probably enhanced by sediment built up behind check dams and presence of vegetation. This is in agreement with the finding of Hood et al. (2007) that gully channel management interventions with check dams and vegetation increase lag to peak mainly for small and short storms duration and dry soil conditions.

4.5. Peak flow discharge

In all gullies peak flow discharges are smaller at the lower sections (Table 3). This is due to runoff loss as infiltration between the inlet and outlet of the gully reaches. The reduction is larger in gullies with check dams and vegetation (8–17%) than in gullies without any treatment (5–6%) (Table 3). The larger reduction in gullies with check dams and vegetation can be attributed to the sediments deposited behind the check dams and to the presence of vegetation in the channel that reduce runoff velocity and increase infiltration. Earlier studies have also documented the decreasing response of peak flow discharge to check dams and vegetation (Hood et al., 2007; Huang and Zhang, 2004; Namadi et al., 2014; Potter, 1991).

4.6. Runoff volume

The reason for the reduction of runoff volume at the lower sections (Table 3 and Fig. 5) is explained by infiltration of runoff between the upper and lower sections. This reduction varies for different runoff events within each gully reach which can be explained by soil moisture content and rainfall intensity (Descheemaeker et al., 2006; Molina et al., 2009). Comparisons of
runoff volume reduction between different gully reaches have depicted that significant proportion of discharge volume was abstracted in the gullies treated with check dams and vegetation (8–18%) (Table 3 and Fig. 9). This is explained by the sediments trapped and vegetation growth as a result of check dam construction in the gullies. Several studies demonstrated the marked effects of physical and biological soil and water conservation on runoff volume reduction by increasing infiltration rates (e.g. Amare et al., 2014; Borst and De Haas, 2006; Hood et al., 2007; Huang et al., 2012; Huang and Zhang, 2004; Lacombe et al. 2008; Molina et al., 2009; Nyssen et al., 2010; Potter, 1991; Taye et al., 2013; Xu, 2005; Xu et al., 2013; Zhang et al., 2014), eventually resulting in the rise of groundwater levels (e.g. Alderwish, 2010; Huang et al., 2012; Parimala Renganayaki and Elango, 2013). Moreover, gully erosion at downstream (Tebebu et al., 2010) due to the greater runoff discharge at the lower section of a stream (Easton et al., 2010) can be halted through installation of check dams combined with vegetation in gullies. The positive effects of check dams on the abstraction of runoff were also deduced indirectly from reclaiming of gully segments by farmers and increased crop yields after construction of check dams (Nyssen et al., 2010; Xiang-zhou et al., 2004). Moreover, the effects of gully treatments on catchment water balance in Northern Ethiopia is noteworthy as gully density in the region is very high (on average 2.52 km km $^{-2}$) (Frankl et al., 2013) and a large fraction of these have been treated by SWC measures. Hence, the result of this study indicates that implementation of check dams in gullies will have a considerable effect on catchment hydrology by increasing infiltration which then improves groundwater recharge and base flows.

5. Conclusions

In North Ethiopia, the implementation of check dams in gullies over the last three decades has contributed to environmental amelioration. Besides soil loss reduction and favouring vegetation growth, check dams also influence hydrological properties in gullies and at watershed scale. The present study has confirmed the hydrological effects of check dams after analyzing lag times, peak flow reduction and volume reduction of runoff along gully reaches. Variations in different discharge parameters were found within and among gully reaches with and without management interventions in two dominant lithologies (sandstone and limestone). In sandstone lithology, gully treatment increase lag times (lag to initiation, lag to peak and lag to end of runoff) as compared to untreated gullies, which demonstrates the significant effects of check dams and the consequent sediment deposition and vegetation growth. But for different rainfall intensity and soil physical properties of treated and untreated gullies lag time to runoff initiation and to peak were larger in untreated gully. This indicates that lag times are not only affected by management interventions but also by soil physical properties of the channel bed and rainfall intensity. Hence, it is difficult to draw general conclusion on the effect of gully treatment on runoff lag times at the lower sections of gully reaches in limestone areas.

Check dams, sediment deposition in the channel and vegetation growth are responsible for the significant variations in the peak flow reduction between gully sections with and without intervention. Generally, this reduction is larger in treated gullies (8–17%) than in gullies without treatment (5–6%). An increase of channel bed roughness resulting from gully treatment reduces peak flow discharge at lower sections of gully reaches by reducing runoff velocity and increasing infiltration.

Whether gullies are treated or not, runoff volume decreases at lower sections of gullies if side runoff is diverted. Installing check dams increases the magnitude of runoff volume reduction. In the present study, runoff volumes were significantly reduced in gullies with check dams and vegetation (8–18%) as compared to the untreated gullies (4–6%) within and across lithologies. We conclude that gully management with check dams and the subsequent sediment build up and vegetation growth results in a significant reduction of runoff in gullies by increasing infiltration. This eventually may leads to recharge of groundwater and improves base flows to streams and reservoirs during the dry season. But further investigation is required to verify the effects of check dam construction in gullies on runoff characteristics at the outlet of catchments and on river baseflows. Moreover, as the present study was conducted in a semi-arid area where soils are less saturated, we cannot conclude the same for humid and sub-humid areas, but we recommend replication of the study in such environments.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2016.12.019.

References
