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# CATCHMENT REHABILITATION AND HYDRO-GEOMORPHIC CHARACTERISTICS OF MOUNTAIN STREAMS IN THE WESTERN RIFT VALLEY ESCARPMENT OF NORTHERN ETHIOPIA

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## ABSTRACT

The catchments in the western Rift Valley escarpment of northern Ethiopia are highly responsive in terms of hydro-geomorphic changes. With deforestation, dense gully and scar networks had developed by the 1980s on the escarpment between the towns of Alamata and Korem, transporting huge amounts of runoff and sediment down to the fertile and densely populated Raya Valley. To reverse this problem, catchment-scale rehabilitation activities were initiated in the mid-1980s. In this study, we examine the major hydro-geomorphic response of streams after catchment rehabilitation. Scar networks in 20 adjacent catchments were mapped on Google Earth imagery of 2005, and their density was explained in terms of its corresponding Normalized Difference Vegetation Index and slope gradient. Soil and water conservation measures and vegetation recovery have reduced discharge and sediment flow which in turn resulted in various hydro-geomorphic changes. In a multiple regression analysis, scar density was negatively related with Normalized Difference Vegetation Index and positively with average gradient of very steep slopes ($r^2 = 0{\cdot}53$, $p < 0{\cdot}01$, $n = 20$). The size and amount of sediment supply to streams decreased, and various channel adjustments occurred. Notably, previously braided streams have changed to single thread streams, lateral bars have been stabilized and stream channels are narrowing and incising. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: scar density; NDVI; incision; northern Ethiopia; stream adjustment; land use change

## INTRODUCTION

Land degradation is a major problem in the Tigray region of the northern Ethiopia (Nyssen *et al*., 2008; Gebresamuel *et al*., 2009). This is mainly due to deforestation, overgrazing, impoverishment of the farmers, erosive rains, steep slopes (Nyssen *et al*., 2004) and limited agricultural intensification (Nyssen *et al*., 2008). The severity of land degradation in this region is mostly evident in several hydro-geomorphic features, including dense gully and river networks (Frankl *et al*., 2011; Yitbarek *et al*., 2012).

To reverse this problem, different rehabilitation activities, composed of physical structures and reforestation measures including establishment of exclosures on highly degraded steep slopes, have been carried out in the region since the mid-1980s (Mengistu *et al*., 2005; Descheemaeker *et al*., 2006a; 2006b; Nyssen *et al*., 2007; Munro *et al*., 2008). Stone bunds, terraces, soil bunds, trenches and check dams were among the commonly used physical structures (Nyssen *et al*., 2007), whereas the reforestation measures included both local and exotic species.

As a result, significant changes have been registered in the region (Pender & Gebremedhin, 2006; Nyssen *et al*., 2007). A study by Descheemaeker *et al*. (2006a) on small exclosed catchments showed a significant reduction of runoff after rehabilitation. According to these researchers, the amount of runoff from rehabilitated exclosures becomes negligible when the vegetation cover surpasses 65%. Nyssen *et al*. (2010) in their turn found a reduction of direct runoff volume by 81% after catchment management, and Frankl *et al*. (2011) found gully systems to be partially stabilized. On the other hand, a sediment dynamics study at medium-sized catchment scale (100–10,000 km$^2$) with mixed land use and land cover showed that the majority of sediment export occurs during a few short but intensive flash floods. Given the patchy nature of rehabilitation activities, the effect of the soil and water conservation measures implemented in such catchments could not be clearly detected (Vanmaercke *et al*., 2010; Zenebe *et al*., 2013).

Mountain streams respond especially to changes in the bio-physical characteristics of catchments (Montgomery & Buffington, 1997; Liébault *et al*., 2002; Defries & Eshleman, 2004; Lana-Renault *et al*., 2011; Serrano-Muela *et al*., 2013). Deforestation, overgrazing and increased agricultural pressure increase discharge and sediment supply to stream channels. In contrast, when catchments are reforested, the amount of discharge and sediment supply decreases, causing various forms of channel adjustments, namely, channel narrowing, pavement development, stream incision, change of pattern from braiding to meandering and colonization of bars by vegetation (Knighton, 1998; Liébault & Piégay, 2002; Liébault *et al*., 2002; Hooke, 2003; Rinaldi, 2003; Piégay *et al*., 2004; Liébault *et al*., 2005; Schumm, 2005;

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Vanacker *et al*., 2005; Beguería *et al*., 2006; Sakals *et al*., 2006; Boix-Fayos *et al*., 2007; Viles *et al*., 2008; Keesstra *et al*., 2009; Frankl *et al*., 2011; Nadeu *et al*., 2012).

The objectives of this study are to; i) examine the role of integrated catchment-scale reforestation on reduction of land degradation as represented by scar networks; ii) analyse the relationship between land degradation and vegetation cover as well as major topographic variables (slope gradient and slope aspect); and, iii) identify the major stream channel adjustments occurred in response to catchment-scale vegetation cover changes.

## MATERIAL AND METHODS

The area of study (12º22′–12º30′N; 39º27′–39º35′E) expands over 114 km$^2$ in the southern zone of the Tigray Region, as a part of the western Rift Valley escarpment of northern Ethiopia (Figure 1). Its elevation ranges from 1,540 to 3,270 masl. The lithology is composed of Tertiary basalt and consolidated volcanic ash (Dessie, 2003), whereas the geomorphology is characterized mainly by plateaus associated with a steep and strongly dissected escarpment. The study focuses on 20 catchments which, like in many other parts of the region, were severely mismanaged up to the mid-1980s mainly due to deforestation, overcultivation, overgrazing and ploughing on steep slopes. Consequently, networks of dense gullies and scars (incised to the bedrock) developed, transporting huge amounts of water and sediment to the farmlands and settlements in the downstream areas. Therefore, the environment and the livelihoods of rural and urban communities and mainly of Alamata town were threatened. In response to severe flooding downstream, different interventions were carried out to reforest the upper escarpment starting from the mid-1980s: some households were resettled outside the catchments, farming on steep slopes was prohibited, some catchments were exclosed and various soil and water conservation measures were introduced. As a result, the present-day vegetation cover of the catchments has shown different degrees of improvement.

The catchments are characterized by volcanic rocks and shallow soils in the sloping areas. The average slope gradient of the catchments ranges from 31% to 68%, which corresponds to either a steep (30–60%) or a very steep (>60%) terrain (FAO, 2006). The streams drain towards the Raya Valley, a marginal graben of the Rift Valley (Figure 1).

The data used in this study were collected from catchment-scale analysis of topographic maps, remote sensing imagery and field observations. Topographic maps with scale of 1:50,000 were used to delimit the catchment boundaries. A 30-m resolution digital elevation model was used to compute the slope gradient and slope aspect of the catchments.

The Normalized Difference Vegetation Index (NDVI) is among the most common indices widely used to indicate the amount and state of vegetation cover in a given area at a specific time (Myneni *et al*., 1995). It has been widely used by many researchers for measuring and monitoring vegetation cover characteristics (Leprieur *et al*., 2000). In semi-arid regions, NDVI has been used for monitoring land cover change and identifying areas affected by land degradation (Li *et al*., 2004) because NDVI, being a satellite-derived dataset, provides spatially continuous data and yields time series signatures from which temporal patterns, changes and relationships may be extracted (Nicholson *et al*., 1998). The NDVI value indicates the amount and condition of green vegetation available in a pixel. It provides an effective measure of photo-synthetically active biomass. More vegetation cover is represented by higher NDVI values. Hence, the mean NDVI values of each catchment were computed from Landsat

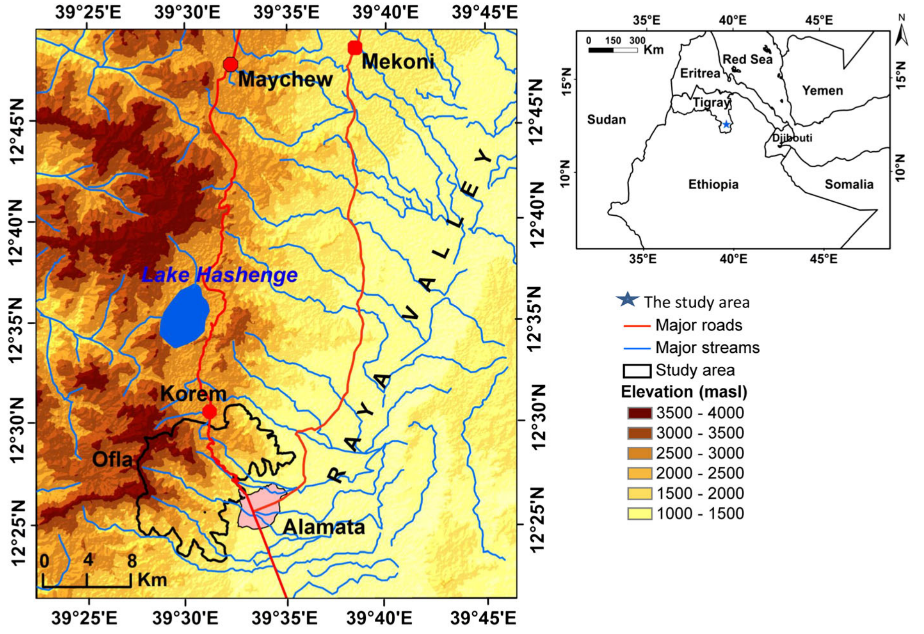

Figure 1. Location of the study area. Oro-hydrography based on Shuttle Radar Topography Mission data (http://srtm.csi.cgiar.org).This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

satellite image (Thematic Mapper) of 25 December 2010 according to the following standard equation:

$$\mathrm{NDVI} = \frac{NIR - Red}{NIR + Red} \tag{1}$$

where NIR and Red are the spectral reflectance values in the near infrared (0·76–0·90 μm) and visible red (0·63–0·68 μm) bands (Myneni *et al*., 1995), respectively. In theory, NDVI values range between −1·0 and +1·0. In practice, however, they generally range between −0·1 and +0·7. Objects such as water, snow and ice give negative NDVI values, whereas bare soils and other background materials produce values between −0·1 and +0·1. Vegetated areas have values greater than zero (Quyen *et al*., 2004).

High-resolution imagery available on Google Earth is increasingly used in geographic studies. For example, Jacob *et al*. (2011) used Google Earth imagery for mapping and measuring treeline elevation in Ethiopia, and Frankl *et al*. (2013) mapped geographic features on Google Earth imagery and made advanced analysis in Geographic Information System. In this study, all scars on the steep slopes of the 20 catchments were mapped on Google Earth imagery (from GeoEye image of 0·6-m resolution acquired in October 2005) and were processed in Geographic Information System to examine the status of land degradation in each catchment. Although both gullies and scars are important visual indicators of land degradation, only scars were chosen to represent changes in land degradation before and after rehabilitation of catchments because they are mainly related to deforestation, whereas gullies may develop because of other factors (Frankl *et al*., 2011). Preliminary observations show that gully erosion is not a straightforward indicator of land degradation because it is dependent on many variables, such as presence and thickness of alluvio-colluvial materials, slope gradient and anthropogenic drainage activities. Further, scars are easily identifiable on high-resolution satellite images. No or very poor vegetation cover, incision till the bedrock, absence of large sinuosity, absence of fill material and low bottom roughness were the major parameters used to recognize the scars. Having prepared the scar density map, it was verified in the field in May 2012, by observing all slopes from vantage points. Then the average scar density of each catchment was explained in terms of average NDVI value and average slope gradient using correlation and multiple linear regression analysis. Pixels corresponding to scars do not have vegetation cover. Hence, they are expected to minimize the mean NDVI values. However, although they are impressive in the landscape, the area occupied by the scars is relatively small, and hence, the impact on the overall NDVI value as well as on the results of the correlation and regression analysis is also expected to be negligible.

Reconnaissance surveys not only help inference of lateral and vertical channel adjustments but also provide representative data and contextual information on channel morphology as well as in-channel and sedimentary features (Downs & Thorne, 1996). In this study, reconnaissance surveys were first carried out in five catchments in February, July and September 2011, and the geological, geomorphological and topographic settings; level of degradation of the catchments; the reforestation and structural methods used in rehabilitating the catchments; the degree of vegetation recovery; and the differences in the characteristics of the channels and the size of bed load depositions both in the abandoned and active channels of the streams were observed. Catchment-scale detailed field observation was executed in all the catchments and along all major streams in May 2012 to identify the degree of: i) channel incision, where availability of new terraces, recently abandoned channels and old stream channel deposits were used as indicators; ii) channel aggradation as represented by sediment deposition in the active channels and or between side bars; iii) widening of channels indicated by exposed tree roots, fallen or leaning trees, destruction of gabions and falling of banks; iv) conversion of single thread channels to braided channels or vice versa; and v) size of boulder depositions in the abandoned and active channels.

Interviews were also carried out with two elderly local farmers who have better knowledge about the rehabilitation processes, situation of the vegetation cover before and after intervention and the hydro-geomorphic changes followed.

## RESULTS

### *Scar Density*

The total length of the scar networks mapped on Google Earth was 34,723 m, whereas the length identified in the field was 33,351 m. The overestimation, or networks that were mapped as scars but are not scars in the field, was 1,866 m (5·6%); whereas the underestimation, or the length of scars that are present in the field but were not mapped in Google Earth, was 494 m (1·5% of the networks). Similarity of scars with gullies and with some footpaths were the major causes for mapping errors, but no systematic change could be observed between field observation (May 2012) and Google Earth imagery (October 2005).

The scar density ranges from 0·04 to 0·69 km/km$^2$ (mean = 0·31, standard deviation = 0·21) and the catchment-averaged NDVI values vary from 0·05 to 0·2 (mean = 0·13, standard deviation = 0·04) (Figure 2 and Table I). The data further indicate some pattern of relationship between the two variables. Relatively low scar density exists in the catchments with better vegetation cover and vice versa. For example, in Gira-Kahsu (catchment 2, Table I), where the most intensive rehabilitation activities were carried out and where the larger part of the catchment is exclosed, relatively high average NDVI value and the lowest scar density are observed.

The incidental repeat photographs of Gira-Kahsu catchment (Figure 3 & catchment 2 in Table I) show a gradual reduction in vegetation cover up to 1975 and a strong increase in 2006. The farmlands on sloping areas of the catchment observed in the 1975 photo were totally covered by shrubs in the 2006 photo. This was also verified in the field. On the other hand, in the

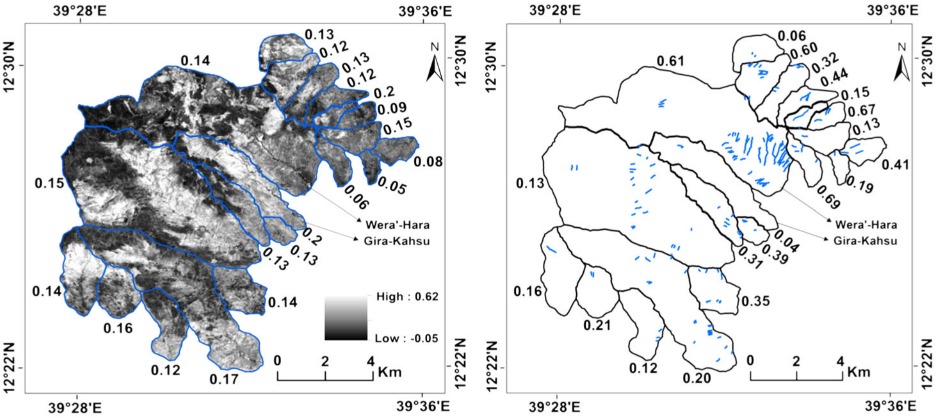

Figure 2. Average Normalized Difference Vegetation Index values (left) and scar density (km/km$^2$) of the 20 catchments (right). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Wera'-Hara catchment (catchment 3, Table I), where farmlands, grazing lands and settlement dominate the upper part of the catchment, less vegetation cover and the largest noticeable scars are observed in the sloping parts of the catchment (Figure 4).

The Pearson's correlation ($r^2 = 0{\cdot}28$, $n = 20$, $p = 0{\cdot}012$) also showed a negative association between scar density and NDVI values (Figure 5, left). No significant relation was observed between average slope gradient of the catchments and scar density. Thus, to differentiate the effect of different slope classes, pixel values of the slope gradient in each catchment were classified in to ten classes according to the FAO (2006) classification system. Of all the classes, only the average gradient of the steepest slopes (>60%) had a positive relationship ($r^2 = 0{\cdot}21$, $n = 20$, $p = 0{\cdot}041$) with scar density (Figure 5, right).

The effect of slope aspect (orientation) of catchments on scar density was also investigated. However, no preferential orientation of scars was observed.

Finally, in a multi-linear regression analysis, scar density was positively related with steep slope gradients (>60%) and negatively with average NDVI values. On the basis of this result, the following equation is used to predict the scar density in relation to the explanatory variables.

$$Sd = 0.04 - 2.99NDVI + 0.01S \quad r^2 = 0.53 \quad p < 0.01 \tag{2}$$

*Where*: Sd, stands for scar density, NDVI for catchment-averaged Normalized Difference Vegetation Index and S for average slope gradient of the steepest slopes (>60%).

Table I. Average Normalized Difference Vegetation Index, average gradient of very steep slopes (>60%) and scar density of the catchments

| Catchment number | Area (km$^2$) | Average elevation (m asl) | Average NDVI | Average slope gradient (%) | Average gradient of very steep slopes (>60%) | Scar density (km/km$^2$) |
|---|---|---|---|---|---|---|
| 1 | 3·6 | 2,246 | 0·13 | 56·4 | 100·1 | 0·31 |
| 2 | 6·6 | 2,227 | 0·20 | 49·4 | 91·3 | 0·04 |
| 3 | 24·7 | 2,470 | 0·14 | 34·3 | 89·9 | 0·61 |
| 4 | 1·8 | 1,920 | 0·06 | 51·1 | 92·2 | 0·69 |
| 5 | 1·1 | 1,857 | 0·13 | 49·0 | 98·4 | 0·39 |
| 6 | 1·0 | 1,692 | 0·05 | 30·8 | 63·7 | 0·19 |
| 7 | 1·6 | 1,623 | 0·08 | 30·4 | 78·0 | 0·41 |
| 8 | 2·2 | 1,868 | 0·15 | 41·4 | 80·1 | 0·13 |
| 9 | 1·2 | 1,718 | 0·09 | 33·2 | 86·4 | 0·67 |
| 10 | 1·1 | 2,053 | 0·20 | 45·0 | 80·1 | 0·15 |
| 11 | 1·8 | 1,977 | 0·12 | 42·4 | 70·0 | 0·44 |
| 12 | 2·4 | 2,120 | 0·13 | 44·9 | 82·0 | 0·32 |
| 13 | 2·9 | 2,193 | 0·12 | 52·8 | 86·0 | 0·60 |
| 14 | 2·2 | 2,087 | 0·13 | 68·0 | 70·3 | 0·06 |
| 15 | 27·5 | 2,530 | 0·15 | 49·4 | 60·0 | 0·13 |
| 16 | 3·3 | 1,946 | 0·14 | 32·9 | 66·6 | 0·35 |
| 17 | 15·8 | 2,212 | 0·17 | 38·6 | 83·3 | 0·20 |
| 18 | 3·5 | 2,096 | 0·12 | 34·6 | 63·1 | 0·12 |
| 19 | 3·0 | 2,279 | 0·16 | 46·7 | 74·5 | 0·21 |
| 20 | 4·4 | 2,438 | 0·14 | 51·0 | 61·0 | 0·16 |
| Mean | 5·6 | 2,078 | 0·13 | 43·9 | 78·9 | 0·31 |
| Standard deviation | 7·7 | 256 | 0·04 | 9·6 | 12·4 | 0·21 |

NDVI, Normalized Difference Vegetation Index.

1937 photo ©IAO

1970 Photo © Larry Workman

1975 Photo © Neil Munro

2006 Photo © Jan Nyssen

Figure 3. The incidental series of repeat photographs of Gira-Kahsu catchment shows expansion of agricultural land up to 1975 and dramatic reforestation thereafter. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

### *Stream Bed Adjustments*

Apart from the differences in scar density, variations were also observed in the field between forested and less forested catchments in terms of: i) size and amount of sediments deposited in their channels; and ii) stream channel adjustments. In many of the less forested catchments (NDVI range of 0·06–0·14, scar density of 0·41–0·69 km/km$^2$) and where grazing and cultivation take place in the upper part of the catchments, deposition of large boulders and aggradation occur in the active channels (Figure 6A). In many of the relatively forested catchments (NDVI range of 0·15–0·2, scar density of 0·04–0·2) with no or less farming and grazing lands in their upper catchment, however, very few small boulder depositions were observed in the active channels, whereas accumulations of large boulders were noticed in their abandoned channels (Figure 6B).

In certain cases, sediments trapped around riverine trees were good indicators of changes in the amount of sediment deposition before and after reforestation of the catchments. For example, the trunks of two of the remnant original trees in Gira-Kahsu catchment (Figure 7) were buried by successive sediment deposits when the catchment was degraded. Consequently, new roots have grown all along the trunk. The stones and boulders trapped in the tree crowns indicate the level up to which sediment was deposited. After reforestation, the channel of the stream incised along the trees and parts of the trunks were exposed. Now, new branches are growing again on the exposed part of the trunks.

Abandonment of previously braided channels in favour of single thread streams (Knighton, 1998), narrowing and lateral displacement of active channels, colonization of lateral bars by vegetation (Boix-Fayos *et al*., 2007) and downstream channel incision (Gordon & Meentemeyer, 2006) were among the most important stream channel adjustments observed in response to improvements in vegetation cover of upper catchments and its subsequent effect on reduction of discharge and sediment flow (Figures 8 and 9).

Figure 4. Scars incised to the bed rock on steep slope mountains with less vegetation cover (Wera'-Hara catchment). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

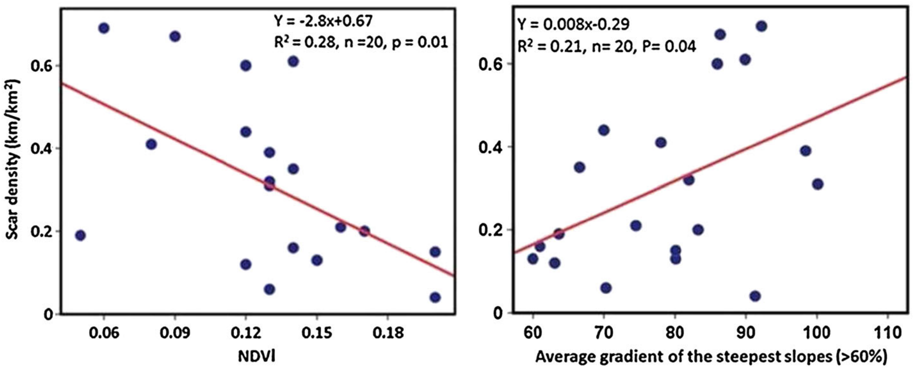

Figure 5. Relationship between Normalized Difference Vegetation Index and scar density (left) and between average gradient of the steepest slopes (>60%) and scar density (right). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

## DISCUSSION

In agreement with earlier research findings in the region (Mengistu *et al.*, 2005; Pender & Gebremedhin, 2006; Nyssen *et al.*, 2008; Meire *et al.*, 2013), the vegetation cover in several catchments has improved thanks to the different management interventions executed since the mid-1980s. Similarly, a study by Gebrehiwot & Van der Veen (2013), in Enderta district of Tigray region showed a substantial increase in vegetation cover of exclosures between 2000 (NDVI = 0·10 to 0·22) and 2008 (NDVI = 0·15 to 0·39). As reported by the elderly people and verified in the field, generally, all types of interventions contributed for the improvements of the vegetation cover of the catchments, although the exclosed catchments and sub-catchments showed better improvements owing to less or no contact with livestock and human beings. However, the average NDVI values of the catchments (Table I) remain relatively low because of: i) the presence of other land covers such as rock outcrops and other land uses such as farmlands, settlement, grazing land or bare lands; and (ii) the relatively high grazing pressure (especially along roads and footpaths) causing sparse vegetation complexes to dominate.

The erosion control measures and vegetation recovery reduced land degradation which, in turn, was followed by various hydro-geomorphic changes. As shown in both the Pearson correlation and multiple linear regression analysis, scar density, which is one of the most easily discernible indicators of the status of land degradation and hydro-geomorphic characteristics of the landscape, significantly decreased with increasing vegetation cover (Figure 5, left). Often, scars now remain as relicts on the slopes, being overgrown by vegetation. This is in line with many studies in semi-arid regions, which showed positive relations between plant cover and NDVI values. For example, Amiri & Sharif (2010), Seperhi (2003) and Khajeddin (1995) found significant relations between NDVI values and field vegetation cover data. This is because when the vegetation cover increases, the NDVI value increases owing to strong reflection of the near infrared bands by the plant cover (Amiri & Sharif, 2010). Conversely, low vegetation cover results in lower NDVI values because of the effect of the background soil (Apan, 1997). The positive association of scar density with very steep slope gradients (>60%) expectedly indicates that these areas are very vulnerable for incision because topographic features such as slope gradient enhance erodibility, showing that steep land is more vulnerable to erosion than flat land (Hudson, 1981).

Similar stabilization of gullies due to the successful implementation of soil and water conservation measures have been reported in the region (Frankl *et al.*, 2012) and in many other semi-arid areas (Grimaldi *et al.*, 2013)

Vegetation cover largely determines runoff and sediment delivery to streams. Initially, in the deforested catchments

Figure 6. Large boulders recently deposited in the active channel of the less forested catchment (A) and the gravelly active channel of the reforested Gira-Kahsu catchment, finding its way between older boulder deposits (B). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

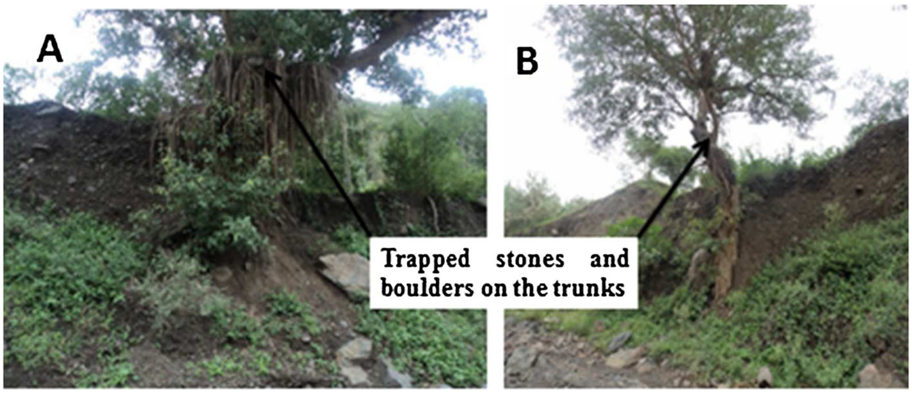

Figure 7. Riverine trees were buried by sediment before the catchment was reforested. Reincision allows to observe the thickness of the sediment deposition and roots that developed in it. Stones and boulders are still trapped in the crowns of the trees. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

(1980s situation), runoff production was high and so was sediment production by the streams (Coulthard & Macklin, 2001). This is evidenced by large boulders present in many of the abandoned channels and by the thickness of flood deposits filling valleys, to the extent of fully covering trunks of riverine trees (Figure 7). Similarly, at present, the less forested catchments are still producing high peak discharges, transporting large boulders and producing huge amounts of sediment.

These findings are in line with similar studies carried out in the region in relation to reforestation and its impact on runoff production and sediment transportation (Descheemaeker *et al*., 2006a, 2006b, Nyssen *et al*., 2009). Bruijnzeel (2004) and Huang & Zhang (2004) also found similar results. In the study area, the runoff and sediment supply to the stream channels have been reduced greatly after reforestation. Consequently, the transport capacity of streams was reduced, and only small boulders and flood deposits of limited thickness were observed in the active channels of the reforested catchments. Worldwide, changes in discharge and sediment load cause channels to adjust their shape and size (Schumm, 1977; Petts, 1979). With reducing discharges and sediment loads, typical changes are the abandonment of the previously braided channel patterns in favour of a single thread stream, lateral displacement and deepening of active channels and stabilization and colonization of lateral bars by vegetation cover. Such changes were widely observed in the streams of the reforested catchments of our study. When sediment load reduction is more important than peak flow reduction, the clear water effect (Boix-Fayos *et al*., 2007) causes previously aggrading channels to incise. The precise impact of long-term variations in discharge and sediment load can best be understood by considering the equations of Knighton (1998):

$$Q^{+} \text{ and/or } Q_s{}^{+} => w^{+}, (w/d)^{+} \tag{3}$$

$$Q^{+} \text{ and/or } Q_s{}^{-} => d^{+} \tag{4}$$

$$Q^{-} \text{ and/or } Q_s{}^{+} => d^{-} \tag{5}$$

$$Q^{-} \text{ and/or } Q_s{}^{-} => w^{-}, (w/d)^{-} \tag{6}$$

in which, the + or − signs indicate an increase or decrease in discharge (Q) and sediment load ($Q_s$) of the streams and their impact on the width (w), depth (d) and width/depth ratio (w/d) of the channels. The four equations conceptualize the general response of stream channels to runoff and sediment load alterations related to changes in catchment vegetation cover. Generally, Equation 3 corresponds to the situation of degraded catchments where high discharge and sediment supply to the streams results in widening of the channels. With high sediment supply, oversaturated flows cause the channels to aggradate (Equation 5). This situation was commonly observed in the most of the degraded catchments and in the catchments that comprise different land use/cover classes. For example, the big boulders shown in Figure 6A, were deposited in 2010 in the Wera'-Hara catchment owing to the existence of very large farmlands, grazing

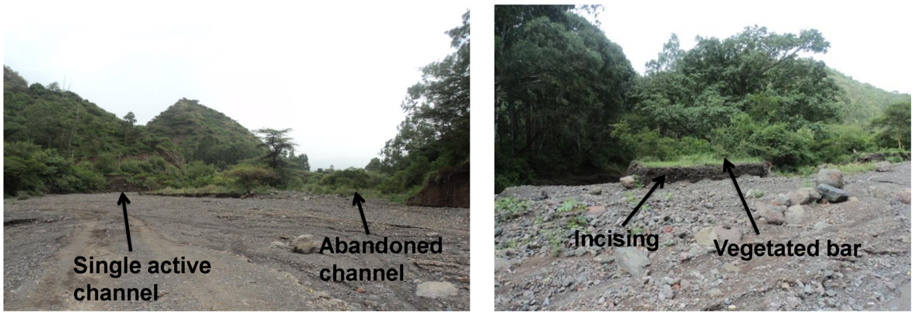

Figure 8. Abandoned channels. The river now flows in one of the preexisting channels and deepens it (B). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

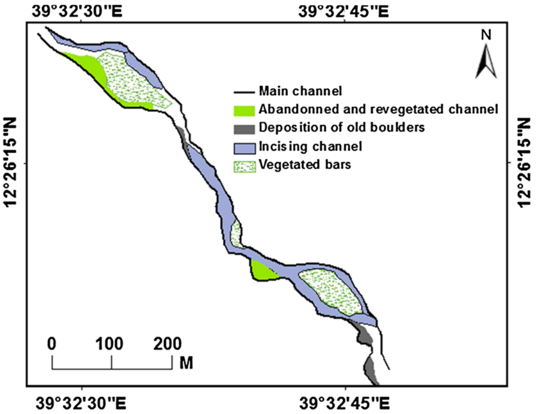

Figure 9. Stream channel adjustments in the lower reach of the Gira-Kahsu catchment. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

lands, settlement and rock out crops in its upper catchment. Reversely, Equations 4 and 6 explain the status of the channels after reforestation where decreased discharge and sediment supply have resulted in incision and less aggradation and thereby reducing the width of the active part of the channels. This corresponds to the situation of the catchments like the Gira-Kahsu catchment where reduced discharge and sediment supply led to narrowing of the active channels (Figure 6B) and incision (Figures 6B, 7A, 7B and 8B).

## CONCLUSION

Overall, the vegetation cover of many catchments in the study area has improved because of the catchment-scale reforestation activities carried out since the mid-1980s. This was followed by many changes in hydro-geomorphic characteristics. On the basis of the results, the following points are concluded: Land degradation as represented by scar density decreases with increasing vegetation cover. A multilinear regression analysis ($r^2=0{\cdot}53$, $p<0{\cdot}01$, $n=20$) showed a negative relationship between scar density and NDVI and a positive relation with the occurrence of naturally vulnerable very steep slope gradients (>60%). The volume and size of sediment transported by the streams are reduced after reforestation. Old boulder deposits in the abandoned channels, thick layers of flood deposits around riverine trees and reduction of size and volume of newly deposited sediment in the active channels were observed in the reforested catchments indicating the impact of the reforestation in reduction of discharge and sediment supply. On the other hand, sediment supply continues unabatedly to the channels in the less reforested catchments. Various stream channel adjustments occurred in response to the changes in discharge and sediment load. Abandonment of many of the previously braided stream channels in favour of single thread streams, stabilization and colonization of lateral bars by vegetation and incision of lower stream channels were observed in the field. Unlike earlier catchment studies in nearby areas where catchments were insufficiently differentiated to demonstrate effects of variable land use, this study has shown that catchment reforestation in northern Ethiopia has led to a remarkable stabilization of the slopes in less than 30 years as well as to narrowing and incising rivers that should be interpreted as signs of a resilient catchment.

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