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Please cite this publication as follows:

Mekonnen, M., Keesstra, S. D., Baartman, J. E. M., Stroosnijder, L., & Maroulis, J. (2017). Reducing Sediment Connectivity Through man-Made and Natural Sediment Sinks in the Minizr Catchment, Northwest Ethiopia. *Land Degradation and Development*, 28(2), 708-717. <https://doi.org/10.1002/ldr.2629>

REDUCING SEDIMENT CONNECTIVITY THROUGH MAN-MADE AND NATURAL SEDIMENT SINKS IN THE MINIZR CATCHMENT, NORTHWEST ETHIOPIA

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Received 7 April 2016; Revised 19 July 2016; Accepted 19 July 2016

ABSTRACT

Man-made and natural sediment sinks provide a practical means for reducing downstream reservoir sedimentation by decreasing soil erosion and enhancing the rate of sedimentation within a catchment. The Minizr catchment (20 km²) in the northwest Ethiopian highlands contains numerous man-made soil and water conservation (SWC) structures such as soil bunds (Erken), fanya juu ridge (Cab) and micro-trenches and natural sediment sinks such as wetlands, floodplains and grassed waterways. These sediment sinks reduce downstream sedimentation into the Koga reservoir, located at the catchment outlet, however, a large quantity of sediment is still reaching the reservoir. This study evaluates the function and effectiveness of both man-made SWC structures and natural sediment sinks in reducing sediment export from the Minizr catchment. SWC structures and natural sediment sinks were digitized using Google Earth Imagery. Sediment pins and vertical sampling through the deposit were used to quantify the amount of deposited sediment. In addition, inflow and outflow of suspended sediment data were used to calculate the sediment-trapping efficacies (STE) of man-made SWC structures (soil bunds and fanya juu ridges) and natural sediment sinks. Results reveal that 144 km soil bunds and fanya juu ridges trapped 7,920 Mg y⁻¹ (55 kg m⁻¹ y⁻¹) and micro-trenches trapped 13.26 Mg y⁻¹, each micro-trench on average trapped 23 kg y⁻¹. The 17 ha floodplain located in the centre of the catchment trapped 9,970 Mg y⁻¹ (59 kg m⁻² y⁻¹), while a wetland with a surface area of 24 ha, located near the outlet of the catchment, trapped 8,715 Mg y⁻¹ (36 kg m⁻² y⁻¹). The STEs of soil bunds and fanya juu ridges, wetlands and floodplains were 54%, 85% and 77%, respectively. Substantial differences were observed between the STE of grassed and un-grassed waterways at 75% and 21%, respectively. Existing man-made and natural sediment sinks played an important role in trapping sediment, with 38% (26,600 Mg y⁻¹) of transported sediment being trapped, while 62% (43,000 Mg y⁻¹) is exported from the catchment and thus enters the Koga reservoir. Therefore, additional catchment treatment measures are required as an integrated catchment scale sediment trapping approach to help reduce sediment loads entering Koga reservoir. Moreover, to maximize the effectiveness of sediment trapping measures, avoid structural failure and ensure their sustainability, regular maintenance is needed. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: soil and water conservation structures; wetland; floodplain; waterway; sediment trapping efficacy; Koga reservoir

INTRODUCTION

Soil erosion by runoff water is a global land degradation problem (Dai *et al.*, 2015; Seutloali and Beckedahl, 2015; Stanchi *et al.*, 2015; Novara *et al.*, 2016; Ochoa *et al.*, 2016). However, it is more severe in developing countries like Ethiopia (Hurni, 2000; Nyssen *et al.*, 2004) and results in significant economic losses (Erkossa *et al.*, 2015). Currently, water erosion is the most serious land degradation threat to the upper part of the Blue Nile basin within the north-western highlands of Ethiopia (Adimassu *et al.*, 2014; Mekonnen *et al.*, 2015b; Ayele *et al.*, 2016). The main causes include erosive high intensity tropical rains, rugged topography, extensive deforestation for fuel wood, expansion of cultivation into unsuitable steeply sloping and erosion prone areas, high population pressure and the lack of integrated catchment management (Zelege, 2000;

Bewket, 2002; Amsalu *et al.*, 2007; Nyssen *et al.*, 2004; Mekonnen and Melesse, 2011; Mekonnen *et al.*, 2014b).

Therefore, a holistic approach is needed to tackle soil erosion in the region (Mekonnen *et al.*, 2014b; Lanckriet *et al.*, 2015; Nyssen *et al.*, 2015; Tesfaye *et al.*, 2015). Soil and water conservation (SWC) structures provide a practical means for reducing soil erosion, enhancing the rate of sedimentation and decreasing local slope gradient (Gebremichael *et al.*, 2005; Mekonnen *et al.*, 2015a). Various soil and water conservation measures have been implemented at large spatial scales by the Ethiopian government and international and national non-governmental organizations. For instance, 2.1 million ha of hillsides and farmlands were covered by SWC structures in the Amhara National Regional State from 2011 to 2013 (Engdayehu *et al.*, 2015), and a further 1.2 million ha in 2014–2015 (BOA, 2015).

Effective sediment trapping (ST) measures can disconnect landscape units from each other, resulting in a decrease in runoff velocity and sediment transport and, subsequently, reduced downstream sedimentation impacts (Mekonnen

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et al., 2014b). This is enhanced by placing barriers and buffers in the catchment, which ultimately reduces sediment connectivity (Fryirs, 2012). According to Baartman *et al.* (2013), man-made structures such as terraces reduce sediment delivery to the catchment outlet. Research has shown that leaving mulch on the soil surface within the catchment can also reduce the amount of sediment being detached (Cerdeira *et al.*, 2015; Keesstra *et al.*, 2016; Prosdocimi *et al.*, 2016).

The Minizr catchment is an important source of water for the Koga reservoir in the northwest highlands of Ethiopia (Figure 1). To trap sediment within the catchment and reduce sediment loads reaching the reservoir, considerable effort was made to implement soil bund (Erken) and fanya juu ridge (Cab) and also micro-trench structures across large sections of the catchment. Over 144 km of soil/stone bunds and fanya juu ridges, and >576 micro-trenches were constructed within the catchment. In addition, existing natural sediment sinks such as wetlands and floodplains occur over large areas of the catchment and are supplementing man-made structures in trapping sediment within the catchment (Figure 1).

Nevertheless, considerable soil is being eroded from the Minizr catchment and transported into the Koga reservoir: annually 43,000 Mg of suspended sediment enters the Koga reservoir (Mekonnen *et al.*, 2016). In order to reduce the sediment load through improving the sediment trapping efficacy (STE) of the SWC structures, it is important to assess the functioning and effectiveness of existing SWC structures. According to Yeshaneh *et al.* (2014), there is a lack of in-depth studies quantifying the volume of sediment being deposited within SWC structures. Previous research demonstrates that terraces play a key role in trapping sediment and disconnecting sediment transfer pathways in a catchment, but very few have been measured (Marchamalo *et al.*, 2016).

Consequently, the objectives of this study in the Minizr catchment, northwest Ethiopia were to: (i) evaluate the

functioning and effectiveness of both man-made structures (soil bund, fanya juu and micro-trenches) and natural sediment sinks (floodplain, wetland and waterways); and (ii) quantify the amount of sediment trapped and stored in these man-made and natural sediment sinks.

MATERIAL AND METHODS

Study Area

The study was conducted in the Minizr catchment in the North-western highlands of Ethiopia (UTM 1255891–1249499 N; 303559–310272 E; Adindan_UTM_Zone_37N, Figure 1) which is a source of water for the Koga reservoir. It covers an area of 20 km² with an elevation range of 2035 m at the outlet to 2283 m.a.s.l. at its highest point on the watershed divide. Slopes in the catchment range from 0–51% (average of 8%), while >80% of the catchment has slopes between 0–8%.

Average rainfall (2013–2015) was 1215 mm y⁻¹, which falls mainly between June and September, and is preceded and followed by 1 month of sporadic, low intensity rain. Average minimum and maximum temperatures are 11 and 26 °C, respectively. The dominant soil types are Nitosols (62%), Eutric Vertisols (30%), Lithic Leptosols (6%) and Chromic Cambisols (2%) (MNREP, 1995). Figure 1 shows the 144 km soil bund and fanya juu ridges implemented in Minizr catchment, a 24 ha wetland located near the outlet of the catchment and a small floodplain area of 17 ha located at the centre of the catchment, which help to trap sediment and reduce sedimentation of Koga reservoir. In the wetland area, Chromic Cambisols dominate. They are developed from alluvial deposits. The soil is very deep, poorly drained with a dark gray to grayish brown, silty clay loam texture, while the floodplain soil is a Eutric Vertisol which is a very deep, poor to very poorly drained, cracking heavy clay textured soil. The floodplain (Figure 1) is 696 m long and

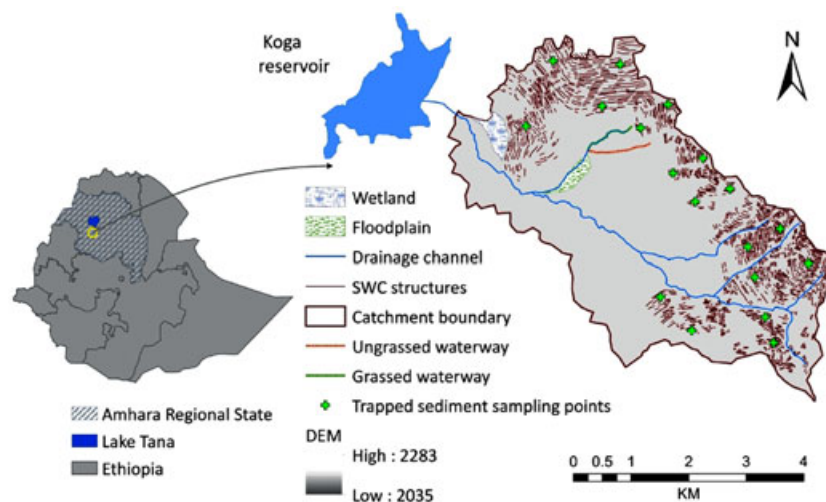


Figure 1. Location map of the Minizr catchment, in the NW Ethiopian highlands of the Upper Blue Nile basin showing the soil and water conservation structures implemented to trap sediment (soil bunds and fanya juu ridges), natural sediment sinks (floodplain, wetland and grassed waterway); and trapped sediment sampling sites. [Colour figure can be viewed at wileyonlinelibrary.com]

243 m wide and is covered with grass, which serves as a grazing area during the dry season.

Land use within the catchment area includes 71% cropping land, 18% grazing land, while plantation, bush land and settlement areas account for the remaining 11%.

Mapping

All SWC structures, land use/cover, wetland and floodplain areas were digitized and mapped from Google Earth Imagery using ArcGIS 10.2.1. A Digital Elevation Model (ASTER DEM 30m; 2009) was used to delineate the boundary of the Minizr catchment and for evaluating its elevation and slope characteristics. A GPS (Garmin 60; 2 m accuracy) helped to collect coordinate points and accurately geo-reference the location of rain gauges, sediment sampling sites and the catchment outlet.

Measuring Trapped Sediment in Soil and Water Conservation Structures

Three types of SWC structures soil bund (Erken), fanya juu ridge (Cab) and micro-trenches have been widely implemented throughout the Minizr catchment (Figure 2). Soil bund and fanya juu ridges were built on farmers' fields, whereas micro-trenches were constructed on degraded grazing lands and integrated with area closures. Figure 3 shows the detailed dimensions of the soil bund and fanya juu ridge.

According to Lakel *et al.* (2010) and Slattery *et al.* (2002), sediment pins and direct measurements of the sedimentary deposit can be used to quantify the amount of sediment in the sediment sinks. In this study, sediment pins and vertical cut measurements of the deposited sediment were used to

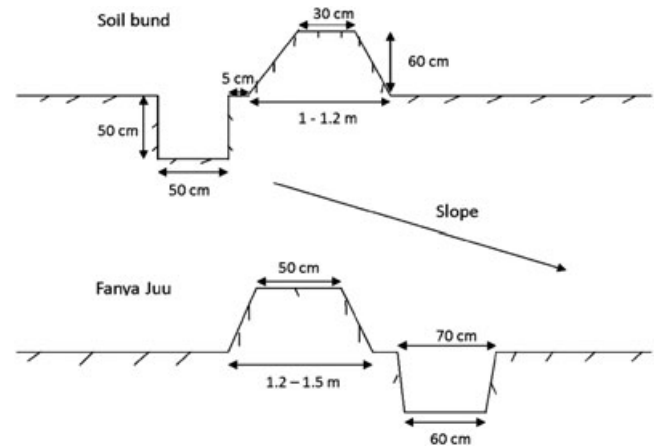


Figure 3. Schematic diagram showing a soil bund (erken; upper) and fanya juu (cab; lower) operate to trap sediment from upslope. Both of them are positioned perpendicular to the slope and runoff direction, thereby maximizing sedimentation and infiltration of surface runoff (MOAR, 2005).

measure the depth of sediment trapped by the SWC structures. Over a two-year period (2014 and 2015), a total of 214 depth measurements were recorded (72 from soil bunds; 72 from fanya juu and 70 from micro-trenches).

When selecting which soil bund and fanya juu ridge to sample, three slope classes were considered: <5% (lower), 5–7% (middle) and >7% (upper). Sampling sites were replicated three times for each of the three slope classes, while three soil bunds and three fanya juu ridges were also evaluated.

The deposited sediment was measured for the nine 30 meter soil bunds. Sediment depth was recorded at four



Figure 2. Sample pictures of a fanya juu (a), micro-trenches (b) and a soil bund (c) structures implemented for sediment trapping at Minizr catchment. [Colour figure can be viewed at wileyonlinelibrary.com]

representative locations (every 10 m distance along each bund) resulting in 36 measurements in 2014 and 72 in 2015. Similarly, nine representative fanya juu ridges (30 m each) were selected. Before the rainy season, 36 sediment pins (10 m spacing, four sediment pins per ridge) were installed, with the depth of sediment measured at the end of the rainy season in 2014 and 2015. In total, 72 depths were collected over the 2 years. Sedimentation width of fanya juu ridges ranged from 0.3–0.9 m with an average of 0.6 m. In addition to sediment pins, vertical cut measurements through the deposited sediment were taken upslope of the fanya juu ridge to increase the accuracy of the data. To calculate the total volume of the trapped sediment, the average depth and width of sedimentation of the two SWC structures (fanya juu and soil bunds) were multiplied by their total length within the catchment.

A sub-catchment containing SWC structures (soil bunds and fanya juu) was selected to evaluate the STE of the structures. Sediment outflow at the outlet of the sub-catchment was measured including sediment trapped by SWC structures within the sub-catchment, which was categorized as inflow sediment. STE was calculated (Equation 1) based on sediment inflow and outflow (c.f. Verstraeten and Poesen, 2000; Mekonnen *et al.*, 2015a) using,

$$STE = \frac{(S_{inflow} - S_{outflow})}{S_{inflow}} * 100 \quad (1)$$

(where:) STE is sediment trapping efficacy (%); S_{inflow} is the sum of the outflow sediment measured at the outlet of the sub-catchment and sediment trapped by SWC structures (kg), and $S_{outflow}$ is sediment measured at the outlet of the sub-catchment (kg).

Micro-trenches on average are 1.5 m long and 0.4 m wide. Thirty micro-trenches were selected with trapped sediment depth determined by measuring the depth of micro-trenches before and after the rainy seasons in 2014 and 2015. In addition, five sediment pins were used in five micro-trenches to measure trapped sediment depth more accurately resulting in 70 sediment depth measurements. To quantify the volume of trapped sediment in a micro-trench, the average measured sedimentation depth was multiplied by the width and length of the structure, which was multiplied by the total number of micro-trenches implemented in the study area.

Measuring Sediment Trapped on the Floodplain

Sediment trapped on the floodplain was quantified using sediment pins and direct measurements of sediment depth (Riihimaki, 2011). Thirty sediment pins were installed inside the 17 ha floodplain area (Figure 1) before the rainy seasons and measured after the rainy seasons in 2014 and 2015. In addition, eight vertical cut measurements of the deposited sediment were performed every year. A total of 76 depth samples (16 direct samples and 60 buried pin depths) were taken over 2 years. To calculate the annual volume of trapped sediment, the average sedimentation depth was multiplied by the floodplain area.

To evaluate the STE of the floodplain, a total of 48 suspended sediment samples (24 composite inflows and 24 outflows in 2014 and 2015) were collected from 24 rainfall events (12 rainfall events each year). Two runoff inflow temporary streams through which the majority of the runoff enters onto the floodplain and one outflow/outlet were used to collect suspended sediment samples. The STE of the floodplain was calculated based on the measured inflow and outflow of sediment (Equation 1).

Measuring Sediment Trapped in the Wetland

Over 3 years (2013–2015), a total of 48 composite suspended sediment samples were collected at four inflow locations, while 48 samples were collected at the main outflow (16 samples each year). The reason being that runoff enters the wetland through four temporary drainage channels and exits the wetland through a single channel (Figure 4). STE of the wetland was calculated based on the measured inflow and outflow of suspended sediment (Line *et al.*, 2008) (Equation 1).

Although suspended sediment samples were collected at the inflow and outflow points of the wetland, it was not possible to estimate the total amount of sediment that enters into the wetland because it was difficult to accurately measure and quantify the inflow runoff entering the wetland through the four temporary inflow channels. Hence, the sediment trapping inefficacy (STI) and the un-trapped sediment that passed through the wetland were used to calculate the trapped sediment contribution using Equations 2 and 3,

$$STI(\%) = 100 - STE(\%) \quad (2)$$

$$TS = \frac{STE(\%) * UTS}{STI(\%)} \quad (3)$$

(where:) TS is the amount of wetland sediment trapped (t), and UTS is the amount of un-trapped sediment that passed through the wetland (t).

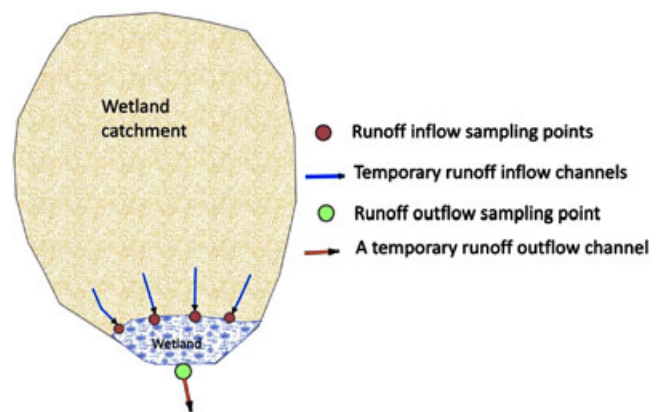


Figure 4. Schematic diagram of the wetland area showing the inflow and outflow of runoff and the locations of the suspended sediment collection sites within the Minizir catchment. [Colour figure can be viewed at wileyonlinelibrary.com]

To quantify the un-trapped sediment that passed through the wetland, both runoff and suspended sediment data were collected at the outlet of the wetland. Runoff depth was measured using a pressure transducer (diver), while channel width was measured using a tape measure. Runoff velocity (m s^{-1}) was measured using the Valeport 'Braystoke' Model 001 current meter. The velocity/area method (FAO, 1993) was used to estimate total runoff discharge (Equation 4), while sediment discharge was calculated from suspended sediment concentration samples (Blanchard *et al.*, 2011) (Equation 5),

$$Q = A \times V \quad (4)$$

$$Q_s = Q \times C_s \times K \quad (5)$$

(where:) Q is runoff discharge in $\text{m}^3 \text{s}^{-1}$; A is channel cross sectional area (m^2) and V is flow velocity (m s^{-1}); Q_s is sediment discharge (t day^{-1}); C_s is concentration of suspended sediment (g l^{-1}) and K is 86.4, which is the conversion coefficient.

Measuring Suspended Sediment in a Grassed Waterway

Grassed waterways are areas where runoff concentrates over grassed areas rather than on bare erodible soil. Grasses enhance infiltration of the runoff and their roots bind the soil and help protect it from erosion. They also help to reduce sediment transport through decreasing flow velocity (Dermisis *et al.*, 2010; Fiener and Auerswald, 2006; Mekonnen *et al.*, 2015b) and are very efficient at filtering runoff and contributing to nutrient and sediment deposition. Both grassed and un-grassed waterways discharge runoff within the Minizr catchment. Therefore, two natural waterways, one covered with grass (grassed waterway) and one devoid of grass cover (un-grassed waterway) were investigated for this study.

To evaluate the suspended sediment load reduction and STE of both waterways, 60 suspended sediment samples (30 inflow and 30 outflow) were collected in 2014 and 2015 in both the grassed and un-grassed waterways with their STEs calculated using Equation 1. The grassed and un-grassed waterways were located at the outlet of two small adjacent catchments covering an area of 2.12 and 2.18 km^2 , respectively. The catchments have similar rainfall, soil type, land use/cover and slope characteristics. The grassed waterway is 1023 m long while the un-grassed waterway has a length of 1016 m, both with an average width ranging from 2.6–3.0 m (Figure 1).

Dry Mass and Sediment Density Calculation

To convert the trapped (deposited) sediment volume to dry sediment mass, the density of the trapped sediment was estimated using the cylindrical core method (McKenzie *et al.*, 2002; Mekonnen *et al.*, 2015a). Six samples from the floodplain, six from micro-trenches and 12 from SWC structures, each of 100 cm^3 , were collected. The samples were oven dried at 105 °C in the laboratory for

24 h, with dry sediment calculated by weighing the dry sediment and subtracting it from the wet sediment mass. Dry mass of the collected suspended sediment samples at the inflow and outflow locations of the wetland, floodplain and waterways was determined in a similar manner. Density was calculated by dividing the dry sediment mass by volume.

Statistical Analysis

Data analysis was performed using Microsoft Excel and IBM SPSS statistics 22 software. ANOVA was run to evaluate differences in sedimentation rates for the different slope classes (upper, middle and lower) in the catchment and to compare the means of trapped sediment by soil bund and fanya juu ridges.

RESULTS

Sediment Trapped by Soil and Water Conservation Structures

In the Minizr catchment, there are 144 km of soil bunds and fanya juu ridges. Overall, the mean measured rate of sedimentation from the sampled soil bunds and fanya juu ridges was 0.053 $\text{m}^3 \text{m}^{-1} \text{y}^{-1}$ or 55 $\text{kg m}^{-1} \text{y}^{-1}$, with an average depth of 0.09 m. Furthermore, the rate of sedimentation was not significantly different at $p < 0.05$ in the upper, middle and lower parts of the catchment and between the soil bunds and fanya juu ridges (Table I). The total annual sediment trapped was 7,620 m^3 or 7,922 Mg (using an average bulk density of 1.04 g cm^{-3}), resulting in a STE of 54%. All micro-trenches (576 in total) constructed on grazing lands trapped 13 $\text{m}^3 \text{y}^{-1}$ or 13.26 Mg y^{-1} (using an average bulk density of 1.02 g cm^{-3}), with each individual micro-trench trapping 23 kg of sediment annually.

Sediment Trapped on the Floodplain

Over 2014 and 2015, the average inflow, outflow and sediment trapped by the floodplain were 15.9, 3.7 and 12.2 g l^{-1} , respectively, with STE calculated at 77%. Thus, a total of 12,950 Mg y^{-1} of soil was eroded from the upper catchment and transported onto the floodplain. On the 17 ha floodplain, 8,670 m^3 or 9,970 Mg of sediment (using a bulk density of 1.15 g cm^{-3}) was trapped at a sediment depth of 5.1 cm, and an average sedimentation rate of 59 $\text{kg m}^{-2} \text{y}^{-1}$. Although 77% of the inflow sediment was trapped, 23% was transported downstream through the floodplain, which amounts to 2,590 $\text{m}^3 \text{y}^{-1}$ or 2,980 Mg y^{-1} .

Sediment Trapped in the Wetland

In the wetland, over the 3 years (2013–2015), the average inflow, outflow and trapped sediment was 6.7, 1.0 and 5.7 g l^{-1} , respectively, with the STE of the wetland being 85%. The average annual volume of sediment trapped and accumulated in the wetland was 8,715 Mg with a

Table I. Catchment sedimentation within a sample of fanya juu and soil bund structures

Structure ^a	Position in the catchment ^b	Sediment depth ^c (m)	Total sedimentation ^d (m ³ 30 m ⁻¹)	Rate of sedimentation ^e	
				(m ³ m ⁻¹ y ⁻¹)	(kg m ⁻¹ y ⁻¹)
Fanya juu	Upper	0.11	1.92	0.064 ^a	65.28 ^a
Fanya juu	Middle	0.09	1.68	0.056 ^a	57.12 ^a
Fanya juu	Lower	0.10	1.74	0.058 ^a	59.16 ^a
Soil bunds	Upper	0.08	1.20	0.040 ^a	40.80 ^a
Soil bunds	Middle	0.10	1.50	0.050 ^a	51.00 ^a
Soil bunds	Lower	0.11	1.65	0.055 ^a	56.10 ^a
Average	–	0.09	1.60	0.053	55.00

^aAverage sedimentation width is 0.6 m (fanya juu); 0.5 m (soil bund) and ditch length is 30 m.

^bPosition and slopes in the catchment; Upper (>7%), Middle (5–7%) and Lower (<5%) slopes.

^cTwo years average deposited sediment depth.

^dTwo years average sediment deposited behind 30 m structures.

^eTwo years average rate of sedimentation.

^aSignificance test of mean difference among treatments at $p < 0.05$, which shows a non-significant difference

sedimentation rate of $36 \text{ kg m}^{-2} \text{ y}^{-1}$. The remaining 15% of the sediment or $1,540 \text{ Mg y}^{-1}$, was annually transported downstream through the wetland. Therefore, $10,250 \text{ Mg y}^{-1}$ of soil was eroded from the upper catchment and transported into the wetland.

Sediment Trapped in Waterways

The average inflow, outflow and trapped sediment over 2014 and 2015, respectively, was 5.6, 1.4 and 4.2 g l^{-1} (grassed waterway) and 5.6, 4.4 and 1.2 g l^{-1} (un-grassed waterway); with STEs of 75% and 21% for the grassed and un-grassed waterways, respectively. The grassed waterway reduced suspended sediment content of the runoff three times more than the un-grassed waterway. This is clearly evident in Figure 5 which shows the junction between low sediment-laden runoff at the end of the grassed waterway on the left (a), and the high sediment-laden runoff at the end of the un-grassed waterway (b) on the right.



Figure 5. Difference in sediment content in the runoff is reflected in differences in sediment loads at the junction between the grassed (a) and un-grassed (b) waterways. [Colour figure can be viewed at wileyonlinelibrary.com]

DISCUSSION

Sediment Trapping by Man-made Soil and Water Conservation Structures

In the Minizr catchment, the rate of sedimentation caused by soil bunds and fanya juu ridges, was on average $55 \text{ kg m}^{-1} \text{ y}^{-1}$ with STE 54%. This finding agrees with Lecce *et al.* (2006), who found drainage ditch sedimentation rates ranging from 12.5 to $88.8 \text{ kg m}^{-1} \text{ y}^{-1}$ in North Carolina.

However, according to Gebremichael *et al.* (2005), in the northern part of Ethiopia (Dogua Tembien district), the rate of sedimentation behind stone bunds was $119 \text{ kg m}^{-1} \text{ y}^{-1}$, which is much higher than the results obtained in this study. Differences in the rate of on-site soil erosion can significantly affect the inflow of sediment into the structures. Soil erosion in the Dogua Tembien district was much higher ($57 \text{ Mg ha}^{-1} \text{ y}^{-1}$) than in the Minizr catchment ($21.5 \text{ Mg ha}^{-1} \text{ y}^{-1}$). In general, SWC structures constructed within fields were found to trap large amounts of sediment and made a major contribution to the reduction of sediment entering the Koga reservoir at the catchment outlet.

Soil and water conservation structures reduce the slope gradient of farmland by forming bench terraces as a result of sediment accumulation (Gebremichael *et al.*, 2005; Mekonnen *et al.*, 2015a). In the study area, even though no statistically significant difference was found in the rate of sedimentation between soil bunds and fanya juu ridges at different slopes, 20 year old fanya juu form high sediment ridge lines because the trapped sediment have gradually converted them into bench terraces (Figure 2a). This decreased average slope gradients by 2.7%. However, soil bunds do not alter the slope gradient largely because the trapped sediment is buried inside the ditch instead of forming a sediment ridge in front of the structure.

Sediment Trapping - Natural Sediment Sinks

In the study area, natural sediment sinks played an important role in trapping sediment and reducing downstream reservoir sedimentation. The 24 ha wetland located near the outlet of the Minizr catchment (Figure 1) trapped $8,715 \text{ Mg}$ of

sediment annually at an average sedimentation rate of $36 \text{ kg m}^{-2} \text{ y}^{-1}$ with a STE of 85%. This result agrees well with the literature. Braskerud (2001) found for constructed wetlands in southeast Norway, sedimentation rates of $14\text{--}121 \text{ kg m}^{-2} \text{ y}^{-1}$. Elder and Goddard (1996) obtained a STE of 80% at the Jackson Creek wetland in Wisconsin, while the Imperial Valley wetland in California had a STE of 97% (Kadlec *et al.*, 2010). Other constructed wetlands revealed STEs of 71–90% in southern Brazil (Sezerino *et al.*, 2012), and 72–88% in North Carolina (Line *et al.*, 2008). Variations in these ranges are largely because of the natural morphology and size of the wetlands and vegetation species composition and diversity, which all have an important influence on the STE of the wetland in reducing erosion and enhancing deposition (Berendse *et al.*, 2015; Braskerud, 2001; Mekonnen *et al.*, 2015b).

According to Keesstra (2007) and Keesstra *et al.* (2009), sediment deposition on a floodplain depends on the location of the floodplain within the catchment and also on the width and land cover of the floodplain. In addition, sediment influx from hillslopes and the intensity of rainfall, all play a role in governing the potential of a floodplain or wetland to trap incoming sediment. In this study, a 696 m long and 243 m wide floodplain, which was covered with grass, trapped 9,970 Mg of sediment annually with a STE of 77% and an average sedimentation rate of $59 \text{ kg m}^{-2} \text{ y}^{-1}$. This result is in line with Brunet and Astin (2008), who found sedimentation rates on floodplains in southwest France ranging from $0.02\text{--}75 \text{ kg m}^{-2} \text{ y}^{-1}$.

Sediment load reduction in grassed waterways ranged from 65% (Dermisis *et al.*, 2010) to 97% (Fiener and Auerswald, 2003). In this study, sediment discharge decreased by 75% between the grassed waterway inflow and outflow. Sediment reduction was considerably higher in grassed waterways than in un-grassed waterways (21%). In addition to trapping sediment, grass cover decreased the propensity for scour, deepening and widening of the waterway by erosion, further reducing the sediment yield from the catchment area.

Although the wetland plays an important role in trapping sediment, floodwaters will inundate the wetland, which over time, will be converted into farmland because of the persistent sediment accumulation. According to Wang *et al.* (2014), watershed management designed to reduce sediment input into the wetland may aid in the conservation of natural wetlands. Therefore, emphasis should be given to man-made ST measures on fields in the upper catchment to help trap and reduce sediment input into the wetland.

Agricultural expansion has also strongly affected the existence of the wetland which has been given to landless youths to cultivate and grow crops. They are slowly converting the wetland into farmland by draining the wetland water and ploughing it. This will destroy the wetland and its ecosystem in a very short period of time. As an alternative, instead of cultivating the wetland area for crop production, the youths could use the grass growing on the wetland for livestock fattening, as a means of generating income without affecting

the wetland. Therefore, awareness raising of policy makers, the surrounding farmers and youth associations is needed to sustainably conserve and manage the wetland.

Disconnecting Sediment Transfer Pathways

Connectivity is an emerging issue of a catchment system (Bracken *et al.*, 2015; Parsons *et al.*, 2015), which indicates how well a system transfers substances, such as water and sediment, through it. The combined effect of ST measures both on-site and off-site will reduce the connectivity of the landscape and sediment transfer pathways within the catchment (Mekonnen *et al.*, 2014b).

The possibility for sediment to be trapped within the catchment is enhanced by the appropriate placement of barriers and buffers, which can reduce sediment connectivity (Fryirs, 2012). According to Baartman *et al.* (2013), man-made structures like terraces are reducing sediment delivery to the outlet. Cerda *et al.* (2015) and Keesstra *et al.* (2016) have shown that leaving mulch within the catchment can reduce the amount of sediment transported to the catchment outlet. Furthermore, reducing the input of sediment from roads as a significant sediment contributor (Pereira *et al.*, 2015) to the total sediment budget, is needed as part of an integrated approach to the whole catchment system. In addition, studies on the impact of plant species (Mekonnen *et al.*, 2015b; Novara *et al.*, 2013) and plant species diversity (Berendse *et al.*, 2015), reveal that by effectively managing plant cover, sediment can be trapped more effectively and that soil erosion can be further reduced.

By utilizing scientific agricultural practices, appropriate SWC measures, and the effective management of the land with suitable plant species, sediment yield at the catchment scale can be reduced. In this study, SWC measures and natural sediment sinks (floodplain and wetland) trapped considerable quantities of sediment by disconnecting the sediment transfer paths within the catchment. SWC structures such as Fanya juu, played an important role in disconnecting the landscape by forming ridges because of the accumulated sediment, which further reduced the slope gradient.

Integrated Sediment Trapping

According to Mekonnen *et al.* (2014b), an integrated ST approach at the catchment scale is believed to be the most effective way in helping to increase the STE of ST measures and thereby reducing sediment loads at the outlet of a catchment. On-site ST measures can help maintain sediments on agricultural field sites, while off-site ST measures trap sediments in drainage channels and gullies. Sediments transported from farmlands without being trapped by on-site ST measures can be trapped by off-site ST measures.

In the Minizr catchment, despite the presence of numerous man-made ST structures and natural sediment sinks trapping large quantities of sediment (26,600 Mg), this only amounts to 38% of the total sediment load, with the vast majority (62%) being deposited in the Koga reservoir (43,000 Mg). There are three reasons for this:

- more emphasis is given to managing on-site sediment sources when implementing SWC structures within fields, without addressing gully erosion or riverbank erosion, which are both important sediment sources in the catchment. According to Mekonnen *et al.* (2014a) and Rijkee *et al.* (2015), river bank and gully erosion are severe and represent an important source of sediment.
- Structural SWC measures are not fully supported with vegetative measures such as grass species, which can help improve STE. To effectively trap sediment and ensure the sustainability of ST structures, it is important to combine both vegetative and structural measures (Mekonnen *et al.*, 2014b; Nyssen *et al.*, 2009).
- Lack of regular maintenance and free grazing are causing SWC structural failures, which affect STE and reduce the sustainability of SWC structures.

To effectively trap sediment within the catchment and further reduce sediment entering the Koga reservoir, an integrated ST approach is needed. This includes the following:

- implementing off-site ST measures such as check dams and sediment storage dams inside gullies and within drainage lines as sediment storage dams constructed inside drainage lines and gullies can trap 67–74% of incoming sediment (Mekonnen *et al.*, 2015a),
- implementing riparian zone measures such as establishing buffer zones and planting trees along the river to reduce riverbank erosion, because vegetation causes flow retardation within the channel and on the riverbanks and thus enhances sedimentation (Keesstra *et al.*, 2012),
- managing sediment access paths, and
- conducting regular maintenance of structures and avoiding free grazing.

Using Vegetative Measures Instead of Physical Structures

In the Minizr catchment, 144 km of SWC structures (fanya juu and soil bund) have been constructed in farmlands to trap sediment and thus help reduce soil loss. To construct this length of structure 69, 000 m³ soil was moved from its original location either upslope (fanya juu) or downslope (soil bunds), which involved 25, 000 human labour days (work norm: 175 persons per day per km; MOARD, 2005). This process increased soil instability and facilitated soil loss, in addition to consuming large amounts of labour. To avoid this problem, vegetative ST measures were seen as better alternatives. According to Mekonnen *et al.* (2015b), grass barriers can trap from 20–76% of the inflow sediment on an 8% slope. Moreover, grass barriers can solve livestock feed problems, which is a crucial issue in both the study area and in Ethiopia in general.

CONCLUSIONS

The STE of existing man-made structures and natural sediment sinks were evaluated in the Minizr catchment,

northwest Ethiopia. They play a significant role in trapping sediment and disconnecting sediment transfer pathways. Rates of sedimentation were 55 kg m⁻¹ y⁻¹ for SWC structures (soil bunds and fanya juu), 59 kg m⁻² y⁻¹ on the floodplain and 36 kg m⁻² y⁻¹ in the wetland, while >576 individual micro-trenches can trap 23 kg of sediment annually. Over 20 years old, fanya juu ridges have reduced the average slope gradient by 2.7% forming lines of high sediment ridges. In soil bunds, trapped sediment is buried inside a ditch instead of forming lines of sediment ridges, which reduces its role in changing the gradient of the slope. Wetlands, floodplains, grassed waterways and SWC structures (soil bunds and fanya juu) were found to be effective sediment sinks with STEs of 85%, 77%, 75% and 54%, respectively. Despite 26,600 Mg (38%) of sediment being trapped by both the existing man-made structures (soil bunds, fanya juu and micro-trenches) and natural sediment sinks (wetland and floodplain), there is still 43,000 Mg (62%) leaving the catchment and entering Koga reservoir as suspended sediment. Therefore, additional catchment treatment measures are required as an integrated catchment scale ST approach to help reduce sediment loads entering Koga reservoir. Moreover, to maximize the effectiveness of ST measures, avoid structural failure and ensure their sustainability, regular maintenance is needed.

ACKNOWLEDGEMENTS

The author would like to thank the (Netherlands Fellowship Programme, NFP; CF Number: CF8569/2012) for its financial support and the Amhara National Regional State, Bureau of Agriculture for providing the first author with the opportunity to undertake his PhD research. We also would like to thank Wageningen University for providing advisory services and research facilities (data collection equipment). We would also extend our thanks to Bahir Dar Soil Laboratory Center for providing laboratory facilities. Our sincere thanks go to the farmers and field data collectors for their assistance during the field work. The comments of the two anonymous reviewers and prof. Tammo Steenhuis were greatly appreciated.

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