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SEDIMENT LOSS PATTERNS IN THE SUB-HUMID ETHIOPIAN HIGHLANDS

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ABSTRACT

Controlling soil erosion is important for maintaining land productivity and reducing sedimentation of reservoirs in the Ethiopian highlands. To gain insights on sediment loss patterns, magnitude of peak sediment events, and their contribution to annual loads, hydrometric and sediment concentration data were collected for five years (2010 – 2014) from the 95-ha Debre Mawi and four nested catchments (located 30 km south of Lake Tana). Soil and water conservation practices (SWCPs) consisting of soil bunds with 50-cm-deep furrows were implemented in the third year, which made it possible to examine the effects of SWCPs on peak sediment loads. The results show that a 10-min event causes soil loss of up to 11·4 Mg ha^{-1}, which is 22% of the annual sediment yield. Thirty to seventy-five percent (up to 30 Mg ha^{-1}day^{-1}) of the sediment yield was contributed by the greatest daily flow in each year. The contribution increases to 86% for the two largest daily flows. SWCP interventions reduced sediment loss by half but did not affect the relative contribution of peak events to annual loads. Because of gully erosion, peak sediment loads at the outlet of the entire catchment were greater (up to 30 Mg ha^{-1}day^{-1}) as compared to the nested catchments without gullies (0·5 to 8 Mg ha^{-1}day^{-1}). Consequently, to reduce sediment loss, conservation measures should be designed to decrease runoff during large storms. This can be attained by deepening furrows on unsaturated hillsides and reducing the entrainment of unconsolidated sediment from failed gully banks. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: Africa; erosion; gully; saturation; watershed

INTRODUCTION

Soil erosion is one of the most serious threats to cultivated land and is a critical socio-economic and environmental problem worldwide (Morgan, 2009; Lieskovský & Kenderessy, 2014). It is a key sustainability issue in mountainous regions with shallow soils (Stanchi *et al*., 2015). Erosion can lead to severe land degradation (Meshesha *et al*., 2012) under intensive agriculture, reducing productivity (Lal, 1998) and increasing runoff (Tilahun *et al*., 2015). Controlling erosion caused by water is particularly a serious challenge for land managers in the high-rainfall dominated areas of the world such as in the (sub) humid highlands of Ethiopia. For example, the Blue Nile River alone carries more than 125 million tons of sediment per year from the Ethiopian highlands to the Sudan, and sediment load is still increasing (Omer *et al*., 2015). Because of the high sediment loads, the Roseires Dam in the Sudan has lost more than one third of its storage capacity (Ali *et al*., 2014; Steenhuis & Tilahun, 2014).

Most soil erosion studies in Ethiopia (SCRP (Soil Conservation Research Programme), 2000a; SCRP (Soil Conservation Research Programme), 2000b; SCRP (Soil Conservation Research Programme), 2000c; SCRP (Soil Conservation Research Programme), 2000d; Bewket & Sterk, 2003; Gebremichael *et al*., 2005; Nyssen *et al*., 2009; Haile & Fetene, 2012) and in the Debre Mawi catchment (Zegeye *et al*., 2010; Amare *et al*., 2014) focus on annual soil losses, while sediment loss patterns and the characteristics of peak sediment loads are often overlooked. However, a study by Vanmaercke *et al*. (2010) conducted in the semi-arid areas of Tigray of the northern Ethiopian highlands indicated that the majority of sediment export took place during few flash floods, and this pattern is independent of soil and water conservation practices (SWCPs). In the (sub) humid Ethiopian highlands, the amount of precipitation is greater than the semi-arid areas and falls in a few months. The intensity and kinetic energy of rainfall are also generally greater, which implies that the sediment loss for few rainstorms in the sub-humid Ethiopian highlands could be larger than in the temperate or semi-arid areas (Ruppenthal *et al*., 1996; Hoyos *et al*., 2005).

Studies conducted in various parts of the world have shown that a large proportion of annual sediment loads are lost in a short period during few rainstorms. A study conducted in the USA (Gonzalez-Hidalgo *et al*., 2010) reanalyzed the Universal Soil Loss Equation database of 310 erosion plots and found that 50% of the total annual soil loss was contributed by five of the largest rainfall events. In the Aisa valley experimental station of central-western

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Pyrenees, Romero *et al*. (2012) determined that the soil loss from the three largest events ranged from 25 to 71% of the total sediment loads. Coppus & Imeson (2002) observed sediment loads of up to 15 Mg ha^{-1} for a 30-min event in a semi-arid Andean Valley. In the tropical humid Andean region of Colombia, studies have found that 10% of storm events can account for 89% of annual soil loss, and in other cases, 61% of annual soil loss occurs in three large rainstorms (Ruppenthal *et al*., 1996; Hoyos *et al*., 2005). In Kenya, catchments lose an average of 80% of their sediment in the largest 10% of flows and 41% of the mean annual sediment yield (SY) in the upper 1% of flows (Dunne, 1979). Other studies (Lamoureux, 2002; González-Hidalgo *et al*., 2007; González-Hidalgo *et al*., 2009; Krasa *et al*., 2010; Stumpf *et al*., 2016) have shown similar results entailing the strong impact of large events on annual sediment loads.

Knowledge of the magnitude and pattern of sediment loads during peak runoff events is important in the dimensioning of hydraulic structures including SWCPs. It is also important in ecological applications where maximum sediment concentrations, even for the short term, could harm fish and fauna (Anderson *et al*., 1996). Thus, this study examines the sediment transport patterns, including the occurrence of peak sediment loads, their magnitudes and contribution to annual sediment yield, and the effect of SWCPs on peak sediment transport in the sub-humid Ethiopian highlands, where this information is not available.

MATERIALS AND METHODS

Study Area

This study was conducted in the Debre Mawi catchment (11°18′N and 37°22′E), located near Lake Tana in the sub-humid Ethiopian highlands. The Debre Mawi catchment was chosen because 5 years of runoff and sediment concentration data were available before and after the implementation of SWCPs. The 95-ha catchment has four nested catchments within it: catchment 1 (monitored at Weir-1), catchment 2 (Weir-2), catchment 3 (Weir-3), and catchment 4 (Weir-4) ranging in area from 6 to 10 ha (Figure 1 and Table I). The entire catchment (catchment 5) was monitored at Weir-5. At the five gauging stations established in 2010, streamflow and sediment concentration were monitored for all runoff events at a 10-min interval over a 5-year period. Additional runoff and sediment concentration data were provided by the Amhara Agricultural Research Institute (ARARI).

The slope of the catchment ranges from 1 to 30%, elevation varies between 2·220, and 2·300 m. Long-term mean annual precipitation is 1240 mm (from 1986 to 2006). Main crops produced are cereals such as '*tef*' (*Eragrostis tef*), maize (*Zea mays*), finger millet (*Eleusine coracana*), barley (*Hordeum vulgare*), and wheat (*Triticum*). Legumes such as Haricot bean (*Phaseolus vulgaris*), Fava beans (*Vicia faba*), pea (*Pisum sativum*), and lentils (*Lens*

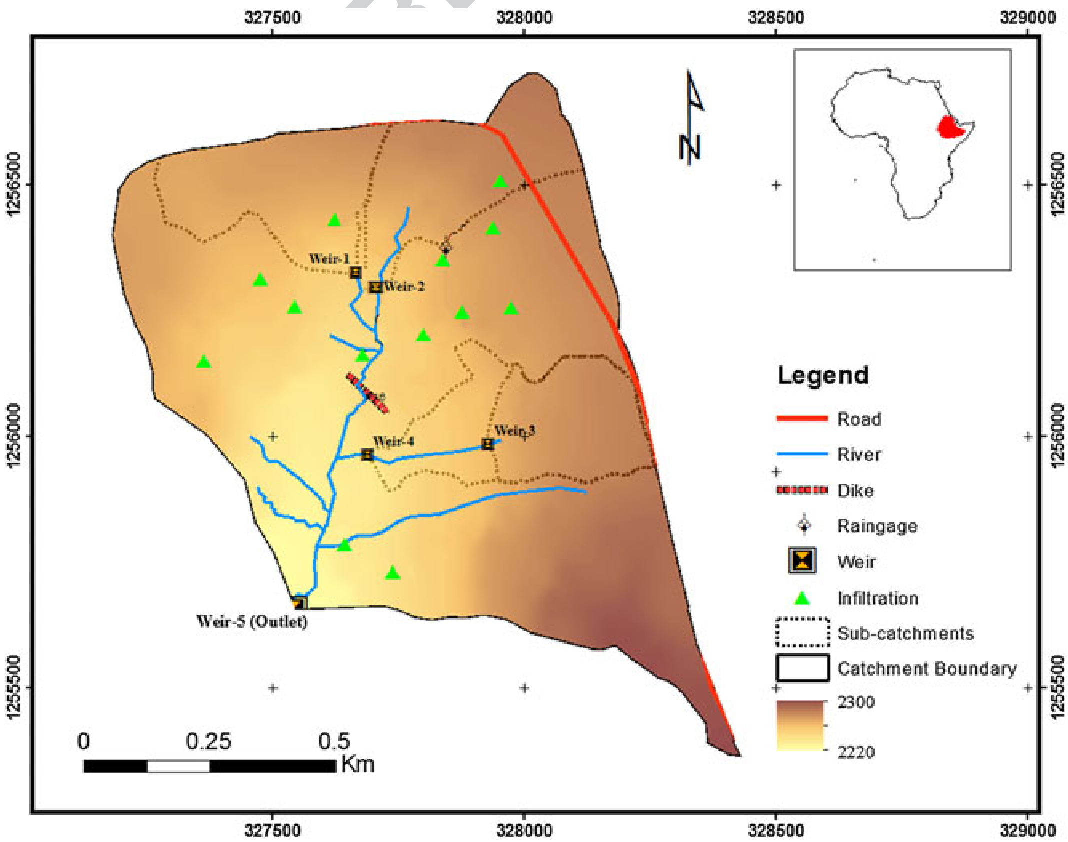

Figure 1. The study area in Ethiopia and location of gauging stations in the Debre Mawi catchment.

Table I. Characteristics of the four nested catchments and the main 95-ha Debre Mawi catchment

Experimental catchments	Area (ha)	Cultivated	Grazing	Forest/Shrub	Gully remarks
Catchment one (Weir 1)	8·8	3·0	5·2	0·6	No gully
Catchment two (Weir 2)	11·0	8·0	2·6	0·4	Stable gully
Catchment three (Weir 3)	6·4	5·1	0·6	0·7	No gully
Catchment four (Weir 4)	10·4	8·0	0·9	1·5	Active stream bank failure
The entire 95-ha catchment Catchment five (Weir 5)	95·0	70·0	14·0	11·0	A number of small[a] gullies (about 15 in number) and a 0·75-ha large active gully near the outlet

[a]Gully classification based on Frevert *et al*., 1993.

culinaris) are also grown in the catchment (Zegeye *et al*., 2010; Tilahun *et al*., 2013).

The main soil types in the catchment are Nitisols, Vertisols, and Vertic-Nitisols (Tilahun *et al*., 2015; WRB. IUSS Working Group, 2015). Nitisols are red, clay-loam soils found in the upper part of the catchment, very deep, well-drained and permeable soils. Vertisols are black soils and cover the lower slope positions. These soils form wide-deep cracks during the dry phase and swell during the rainy season (Tilahun *et al*., 2015). Vertic-Nitisols are reddish-brown, well-drained, permeable soils, located in the mid-slope locations. They have high moisture retention capacity and form cracks when dry (Tebebu *et al*., 2015).

The land use system consists largely of cultivated land followed by grassland and eucalyptus plantations/shrublands (Table I). Grazing land is the main land use type in catchment 1 while the remaining catchments area is mainly cultivated lands. Catchment 2 receives some overland flow from an unpaved road from Bahir Dar to Adet and hence discharge and sediment were not collected in catchment two in 2013 (see Figure S5 for partial view of Debre Mawi catchment).

Before 2012, the SWCPs in the Debre Mawi catchment consisted of traditional drainage furrows implemented by farmers each year after plowing. The Ethiopian government launched an extensive ecological restoration program in 2010, which aimed at doubling agricultural productivity through improving the management of natural resources and agricultural lands. This community mobilization through free labor days was implemented in most community catchments including Debre Mawi. As part of this program, in early 2012, various physical and biological SWCPs were constructed by farmers on most of the agricultural lands in the Debre Mawi catchment. The physical SWCPs include soil bunds with infiltration furrows to a depth of 50 cm, stone-faced soil bunds, and stone bunds. To stabilize the physical SWC structures, different types of tree and grass species were planted on the banks of bunds.

Gully erosion severity is high in the Debre Mawi catchment (Tebebu *et al*., 2010; Tebebu *et al*., 2015). Catchments 1 and 3 do not have gullies; however, there is one small gully (slightly stabilized) in catchment 2, whereas in catchment 4, there is active stream bank erosion. In catchment 5 (outlet), one large and 14 small-sized gullies were identified.

Table II. Location, description, and data used (1981–1993) from the four SCRP research sites (Andit Tid, Anjeni, Hundie Lafto, and Maybar) located in the Ethiopian Highlands (SCRP, 2000a, b, c, d)

Catchment characteristics	Andit Tid	Anjeni	Hundie Lafto	Maybar
Location (Region)	39°43′E, 9°48′N (North Shewa)	37°31′E, 10°40′N (Gojjam)	40°59′E, 9°07′N (Harerge)	39°40′E, 11°00′N (South Wollo)
Catchment area (ha)	477	113	236	113
Elevation range (m a.s.l)	3·040 – 3·548	2·407 – 2·507	1963 – 2315	2530 – 2850
Long-term mean daily Temp (°C)	12·6	16	18·3	16·4
Long term mean annual rainfall (mm/year)	1417	1690	860	1211
Climate according to Thornthwaite	Humid	Sub-humid	Sub-humid	Sub-humid
Main soil types	Humic and Ochric Andosols, Fluvisols, Regosols, and Leptosols	Alisols, Nitisols, and Cambisols	Vertisols, Cambisols, Fluvisols	Phaeozems and Leptosols, Gleysols
Soil degradation status	Medium to high degradation and the catchment has generally moderate soil fertility	Medium to high degradation, generally moderate soil fertility	Medium to high degradation, generally moderate to good soil fertility	The soils of the steeper part of the catchment are highly eroded
Station established	July 1982	March 1984	May 1982	June 1981
Data type used	RF, Q, SSC, and SY	RF, Q, SSC, and SY	RF, Q, SSC, and SY	RF, Q, SSC, and SY
Years of data used	11	10	11	13

Table III. Annual monsoon rain phase runoff (Q, mm), sediment yield (SY, Mg ha^{-1}), and suspended sediment concentration (SSC, g L^{-1}) for the main 95-ha Debra Mawi catchment (w-5) and the four nested catchments: catchment one (W-1), catchment two (W-2), catchment three (W-3), and catchment four (W-4)

Water sheds (W)	2010			2011			2012			2013		
	Q (mm)	SSC (g L^{-1})	SY (Mg ha^{-1})	Q (mm)	SSC (g L^{-1})	SY (Mg ha^{-1})	Q (mm)	SSC (g L^{-1})	SY (Mg ha^{-1})	Q (mm)	SSC (g L^{-1})	SY (Mg ha^{-1})
W-1	111	3·3	3·1	79	3·7	3·4	96	2·4	2·6	50	2·3	1·2
W-2	286	5·8	18·5	197	6·3	13·7	132	3·2	4·3	NA	NA	NA
W-3	121	3·5	5·2	97	4·3	8	74	3·1	2·4	74	3·3	2·6
W-4	163	6·2	12	157	5·5	19·9	140	3·7	5·1	51	3·3	1·8
W-5	314	12·7	70·3	230	13	53·9	62	13·1	9	66	11·5	13·3

[a] *Refers to the mean values of 2010 and 2011 before the implementation of SWC measures.*
[b] *Refers the mean values of 2012, 2013, and 2014 after the implementation of SWC.*
[c] *Percentage change in Q, SY, and SSC was calculated as:* $\frac{(Mean\ \ before\,SWC - Mean\ \ value\ \ after\,SWC)}{Mean\ \ value\ \ before\,SWC}$.

Despite the fact that most soil loss in the catchment is caused by gully erosion (Tebebu *et al*., 2010), gully treatment measures were not implemented.

Data Collection and Analysis

Five years of hydrometric and sediment concentration data from five catchments were used for this analysis. Two years of data (2010–2011) were collected before the implementation of SWCPs and three years data (i.e. 2012–2014) after the implementation. Precipitation, infiltration, stream discharge, and suspended sediment concentration (SSC) data were measured from June to September of each year. Data were not collected in the dry phase, as precipitation, stream flow, and erosion were minimal.

Precipitation was measured at 5-min intervals using a tipping bucket, self-emptying, automatic rain gauge installed in the catchment. Data from the nearby Adet Agricultural Research Center (8 km from the study catchment) and from the National Meteorological Station of Ethiopia (Bahir Dar branch) were used to fill in any missing data.

Infiltration rates were measured in more than 10 fields at different landscape positions, slope classes, and land uses using a 25-cm-diameter single-ring infiltrometer (Tilahun *et al*., 2013). The constant infiltration rate at the end of the test was taken as the infiltration capacity of the area (Cerdà, 1999; Wang *et al*., 2016). Median infiltration rates are considered as a better representation for each of the tests (Tilahun *et al*., 2015).

Manual measurements of flow depth and velocity were conducted by individual observers each 10-min intervals following the onset of rainfall. The five weirs have fixed cross sections following the banks, so that the discharge can be easily calculated (SCRP (Soil Conservation Research Programme), 2000b; Nadal-Romero *et al*., 2008). Surface velocities were determined by the velocity of a float inserted 6–10 m upstream of each weir, by recording time required for the float to reach the weir (Montgomery *et al*., 1999; Dessie *et al*., 2014). Average stream velocities were obtained by multiplying the surface velocity by two thirds (Tilahun *et al*., 2013). Discharge is found as the product of mean velocity and the cross-sectional area. A rating curve was developed for several pairs of stage and discharge measurements at each weir.

For sediment concentration analysis, 1-L water samples were taken at 10-min intervals until the flow declined and the water turned clear (Bosshart, 1997). Suspended sediment concentrations were determined by filtering water samples using Whatman 320-mm-diameter filter paper and weighing the mass of oven dried sediment (Tilahun *et al*., 2013).

Gully erosion was assessed to examine the effect of gullies on the magnitude of peak sediment loads and compare the sediment load generated from catchments with and without gullies. Gully head retreat, gully depth, and width were monitored for a large gully near the outlet of weir 5.

Sediment concentrations were plotted with daily discharge and SY graphs to identify the relationships between sediment concentration patterns and peak discharge events. Then, sediment loss of 10-min events, the largest and two largest daily loads were ranked, tabulated, and the contributions of peak events to annual loads were calculated as a percentage of seasonal loss. Finally, the magnitude of largest loads before and after the implementation of SWC practices was compared and used to evaluate how SWCPs affect peak sediment loads.

To assess whether the Debre Mawi catchment was representative of the Ethiopian highlands, we obtained long-term discharge and sediment data (10–13 years) from Land and Water Resource Center of Ethiopia for four Soil Conservation Research Program (SCRP) catchments: Andit Tid, Anjeni, Hundie Lafto, and Maybar (Figure S1, SCRP (Soil Conservation Research Programme), 2000a; SCRP (Soil Conservation Research Programme), 2000b; SCRP (Soil Conservation Research Programme), 2000c; SCRP (Soil Conservation Research Programme), 2000d). The characteristics of the SCRP catchments are summarized in Table II. T2

RESULTS

Precipitation and Infiltration

In Debre Mawi, rainy season typically occurs from late May to early October. Most precipitation falls during July and August. Precipitation for June–September ranged from 832 to 917 mm over the five years in the period from 2010 to

Table III. (Continued)

Water sheds (W)	2014			Mean before SWC[a]			Mean after SWC[b]			% Change[c]		
	Q (mm)	SSC ($g L^{-1}$)	SY ($Mg ha^{-1}$)	Q (mm)	SSC ($g L^{-1}$)	SY ($Mg ha^{-1}$)	Q (mm)	SSC ($g L^{-1}$)	SY ($Mg ha^{-1}$)	Q	SSC	SY
W-1	67	2·8	1·7	95	3·5	3·3	71	2·5	1·8	26	28·6	45·5
W-2	178	3·6	8·2	242	6·1	16·1	155	3·4	6·3	36	44·3	60·9
W-3	75	3·8	2·7	109	3·9	6·6	74	3·4	2·6	32	12·8	60·6
W-4	114	3·6	4·7	160	5·9	16·0	101	3·5	3·9	37	40·7	75·6
W-5	106	8·2	12·5	272	12·9	62·1	78	10·9	11·6	71	15·5	81·3

2014 (Figure S4), a difference of only 10%. The maximum hourly rainfall intensity was 38 mm h^{-1}, and median infiltration capacity of 29 mm h^{-1} was exceeded by the rainfall intensity in less than 10% of the time. The median infiltration capacity in the upslope (121 mm h^{-1}) was significantly greater ($p < 0{\cdot}05$) than mid-slope (29 mm h^{-1}) and saturated valley bottoms (6 mm h^{-1}) showing the effect of landscape positions on infiltration rates.

Discharge, Suspended Sediment Concentration, and Yield

The average storm discharge from the entire catchment was greater than from the nested catchments (Table III). Installation of SWCPs in 2012 effectively reduced storm runoff (Table III ~~and Figure 3~~). Daily, mean monthly, and annual SSC were greatest at the main outlet (Figures 2 and 3 and Table III) followed by nested catchments 2 and 4. Patterns of SSCs were similar for all five years for all weirs; the sediment concentrations were greatest in the early phase of the monsoon, i.e. in June and early July and gradually declines in August and September (Figures 2 and 3). Similarly, sediment loads from the entire catchment were greater than loads from nested catchments for all the years (Table III). The implementation of SWCPs has resulted in substantial reductions in the SY of the studied five catchments.

Peak Events and Annual Sediment Loads

The sediment loads in each 10-min interval is plotted as a percentage of the annual SY from the five catchments for the five years (Figure 4). The contribution of peak 10-min events for the nested catchments reached up to 32% whereas it reached up to 21% for the entire catchment (Figure 4). It does not appear that the percentage contributions change systematically before and after the SWC implementation (Table IV). The contributions of the 2, 3, 5, 10, and 25th event loads to annual loads for the studied catchments are given in Table IV. For example, 10 largest 10-min events for the nested catchments contributed up to 74% of the annual sediment loads whereas it was up to 79% for the entire catchment. For the 25 largest events, the contribution reached up to 88% and 94%, for the nested catchments and the entire catchment, respectively (Table IV). As the number of events increases, the contribution of each event to annual SY declines (Figure 4).

The magnitude of sediment transported during peak events indicates that these events are the key contributors to annual SY. For example, for the entire catchment, the sediment load of the largest 10-min event was 11·4 Mg ha^{-1}, reaches 16·3 Mg ha^{-1} for two largest events in 2010 (Figure S3). In 2011, the sediment loads of the largest and two largest events (Figure S3) contributed 10 and 17·3 Mg ha^{-1}, respectively. During the study period, the contribution of largest daily sediment loads reached up to 42%, 25%, 62%, 75%, and 73% for catchments 1 to 5, respectively (Table V).

Considerable differences were observed in the volume of sediment loads of peak 10-min events and daily sediment loads before and after the SWC measures (Table IV). For example, after SWC implementation in 2012, the sediment load of the largest events greatly declined to 1 Mg ha^{-1} (Figure S3 and Table V), and the reduction in peak daily loads were up to eight-fold (Table IV). We also observed great spatial and temporal variability of peak daily sediment loads in the catchments. Catchment 1 had a smallest peak SY of 1·5 Mg $ha^{-1}day^{-1}$. The peak daily load of the entire catchment was 30 Mg $ha^{-1}day^{-1}$, which is nearly 4-times greater than peak daily loads generated from the nested catchments. The greatest sediment loads occurred after mid-July, when large sections of the catchment were saturated and produced runoff (Caballero *et al*., 2013; Latron & Gallart, 2007). For example, the largest daily load of catchment 1 in 2010 occurred on 29 July 2010 with a recorded 50 mm of rainfall and 14 mm of storm runoff and a sediment load of 1 Mg ha^{-1} day^{-1} (Table V).

DISCUSSION

Ten-minute and Daily Peak Sediment Loads

Ten-minute Loads

Peak events are important; the largest 10-min sediment loads at the outlet reached 11·4 Mg ha^{-1} and 16·3 Mg ha^{-1} for two largest events in 2010 (Figure S3). Because annual soil losses varied over the 5 years, we plotted the relative contributions (i.e. quotient of 10-min and annual sediment loads) in Figure 4. The greatest 10-min loads contributed 19% in catchment 1 and 21% of the total annual load at the outlet (Figure 4 and Table IV). The ten top 10-min events

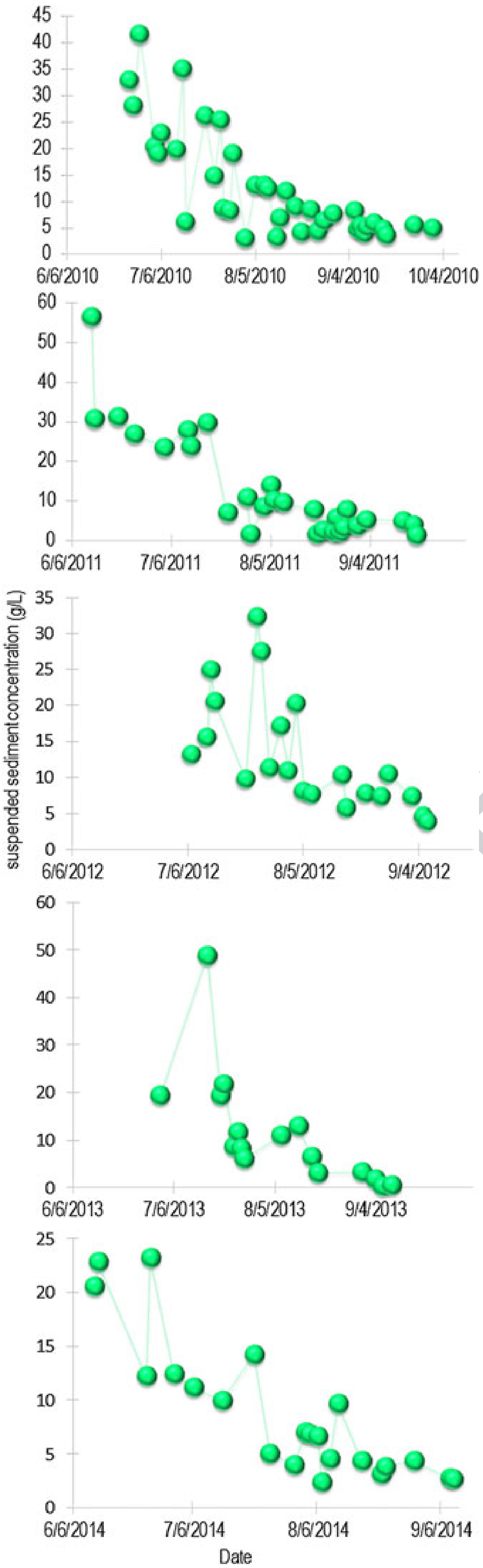

Figure 2. Suspended sediment concentration (daily) for the main catchment from 2010 to 2014.

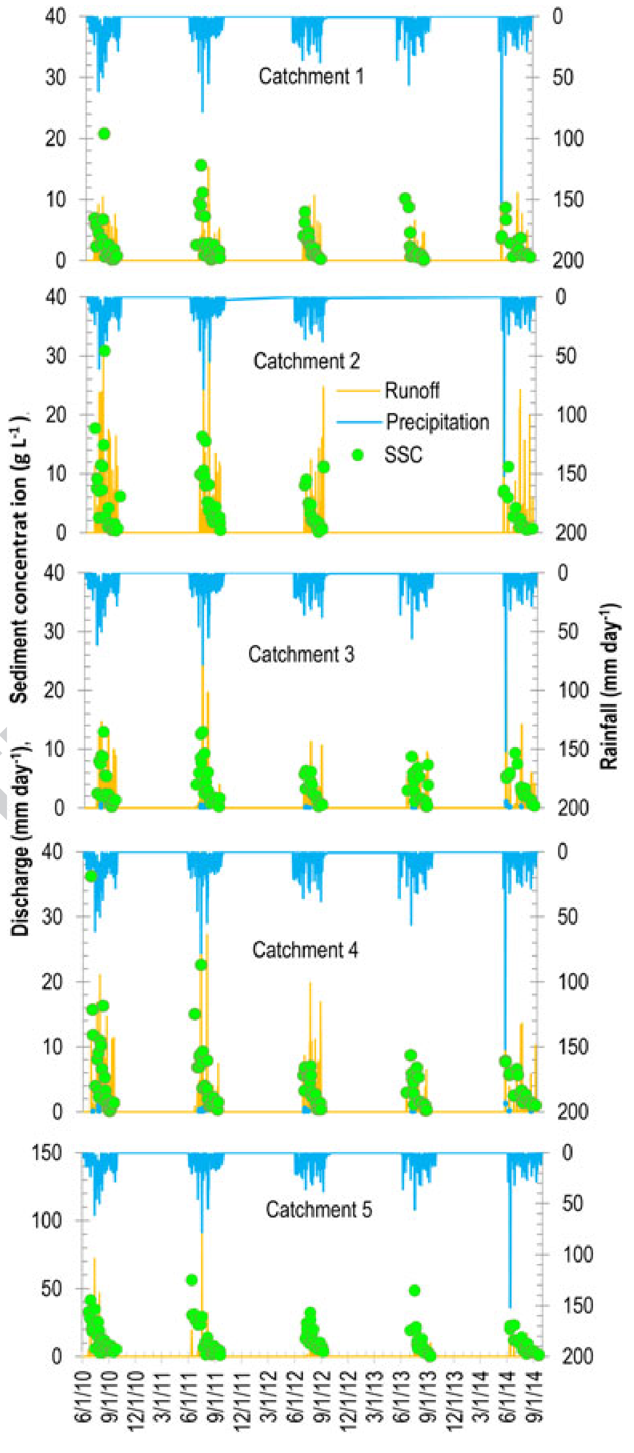

Figure 3. Rainfall, runoff, sediment concentration, and yield relationships for the four nested-catchments and the main catchment (2010–2014).

contributed up to 74% of the annual load in the nested catchments and up to 79% for the entire catchment (Table IV). The 25 top events contributed to a maximum of 88% of the annual loss of the nested catchments and 94% at the outlet (Table IV). Thus, there is an exponential decline in sediment contribution by each subsequent event. From Table IV, it does not appear that the distribution of the peak event contributions to annual loads changed systematically before and after the implementation of SWCPs in 2012 (Table IV).

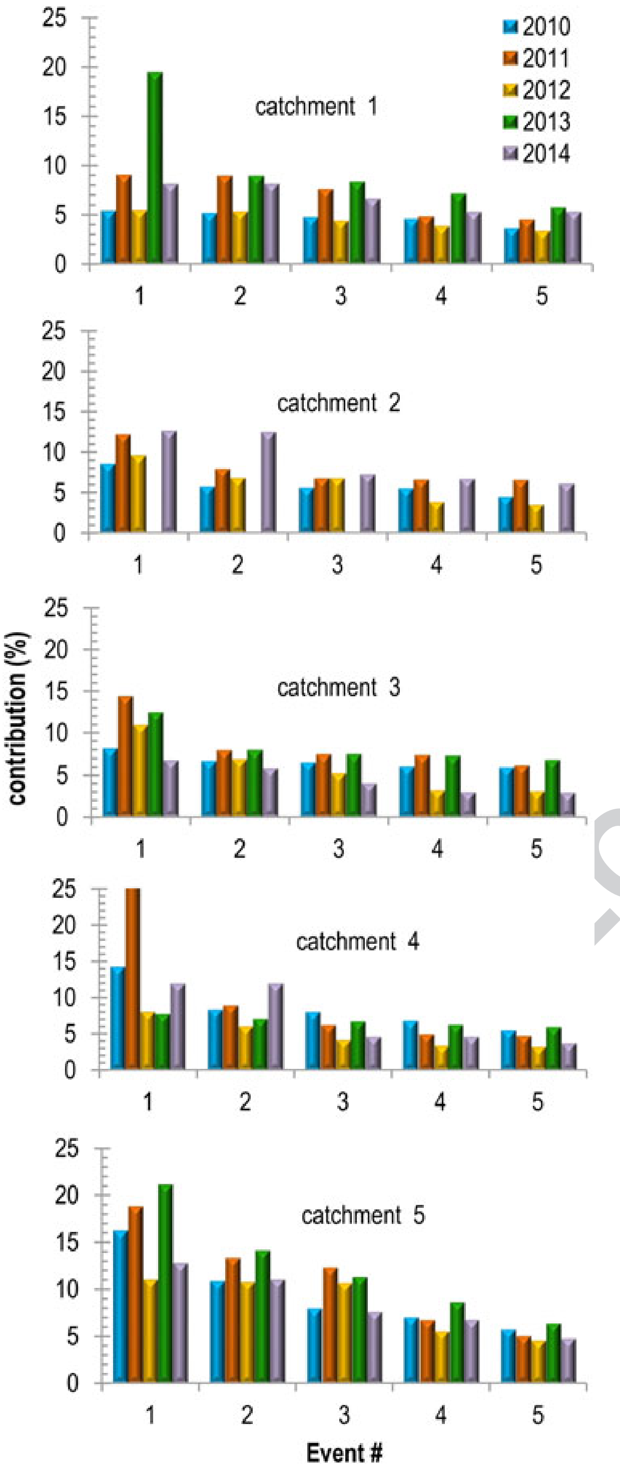

Figure 4. Contribution of 10-min events to annual sediment loads for the five catchments (2010–2014).

Daily Loads

Considerable differences were observed in the daily sediment loads among all catchments. Catchment 1 had the smallest peak daily SY of 1·5 Mg ha^{-1}day^{-1} (Table V). The greatest daily loads of catchment 2, 3, and 4 were 8·1, 7·4, and 14 Mg ha^{-1}day^{-1}, respectively, indicating that the peak daily loads of catchments 2, 3, and 4 were many folds greater than that of catchment 1. Finally, the top daily load at

Table IV. Percentage sediment yield as represented by the 1, 2, 3, 5, 10, and 25 largest events from 2010 to 2014, among the catchments (five weirs)

# of events	Weir 1					Weir 2					Weir 3					Weir 4					Weir 5				
	2010	2011	2012	2013	2014	2010	2011	2012	2013	2014	2010	2011	2012	2013	2014	2010	2011	2012	2013	2014	2010	2011	2012	2013	2014
1	5	9	5	19	8	9	12	10	12	13	8	14	11	12	13	14	31	8	8	12	16	19	11	21	13
2	11	18	11	28	16	14	20	16	20	25	15	22	18	20	16	23	40	14	15	24	27	32	22	35	24
3	15	26	15	37	23	20	27	23	28	32	21	30	23	28	19	31	46	18	21	28	35	44	32	46	31
5	23	35	22	50	33	30	40	31	42	45	33	43	29	42	25	43	56	25	34	37	48	56	42	61	43
10	39	52	37	66	49	46	56	45	60	63	50	65	42	60	37	58	74	37	53	48	63	71	54	79	55
25	68	74	62	86	67	73	74	64	81	80	71	88	60	81	56	77	89	58	79	63	81	88	75	94	74

Table V. Contribution of largest daily sediment loads to sediment yield in the entire Debre Mawi Catchment (catchment 5) and the four nested catchments for largest storms

Study catchments	Date	Daily sediment load ($Mg\,ha^{-1}day^{-1}$)	% contribution of one largest daily sediment load event
Catchment one	7/29/2010	1·0	23
	7/17/2011	1·5	33
	7/12/2012	0·6	18
	7/16/2013	0·7	41
	8/6/2014	0·5	42
Catchment two	7/29/2010	8·1	25
	8/5/2011	6·2	25
	7/13/2012	1·3	17
	2013	NA	NA
	6/25/2014	1·1	22
Catchment three	7/29/2010	1·9	26
	7/17/2011	7·4	62
	7/30/2012	1·0	29
	7/16/2013	0·9	23
	8/6/2014	0·6	19
Catchment four	6/29/2010	4·2	38
	7/17/2011	14·0	75
	7/30/2012	1·3	27
	7/16/2013	0·4	23
	7/21/2014	0·4	22
Catchment five	7/13/2010	25·3	36
	7/17/2011	29·8	55
	8/03/2012	2·1	23
	7/16/2013	9·7	73

the outlet was 30 $Mg\,ha^{-1}day^{-1}$, clearly indicating that the valley bottom generates the most sediment.

In addition, the greater magnitude of peak daily loads occurred before implementation of the SWCPs signifying the effectiveness of SWCPs. Daily sediment loads after SWCPs implementation (Table V) declined to below 1 $Mg\,ha^{-1}y^{-1}$ in catchments 1, 2, 3, and 4 (Figure S3 and Table V) which was substantial reductions in peak daily loads (Table IV). Annual sediment yield for the main watershed decreased from an over 50 $Mg\,ha^{-1}y^{-1}$ before the implementation to 10 $Mg\,ha^{-1}y^{-1}$ after the implementation (Table III). However, suspended sediment concentration was only reduced by 16% at the outlet (Table III).

Sediment Transport Dynamics in Debre Mawi

The sediment load patterns of Debre Mawi catchment is highly episodic; significant amounts of sediment loads occur within a few storm events and the largest sediment load processes of the year occur in a very short period. The elevated sediment concentration (Figure 2) in the early rain phase was caused by the formation of rills in freshly tilled soils (Zegeye *et al*., 2010). Rills formed in the early phase of the monsoon expand in July when rainfall amounts and intensities increase (Bewket & Sterk, 2003), and do not expand in August and September with increased vegetation and less intensive rainstorms (Hasholt & Hansen, 1995; Agassi, 1996; Guzman *et al*., 2013). Lack of relationship between large runoff events and sediment concentrations in August is related to increased vegetation cover and greater soil cohesion, and fully developed (non-eroding) rill network (Dagnew *et al*., 2015; Moges *et al*., 2015).

An interesting question is how soil loss and texture are related. We observed that the soil loss at the outlet in the Debre Mawi catchment is greater than any of the sub-watershed (Table III). One could contribute this easily to the Vertisols that have a finer structure (the mean clay and silt contents of Debre Mawi watershed were 57 and 27%, respectively) (Dagnew et al., manuscript in preparation) than Nitisols in the uplands. This relationship is indirect though. The bottom part of the watershed with the vertisols saturates and saturated vertisols have little cohesive strength allowing gullies to develop. These gullies are the main cause of the elevated sediment concentrations at the outlet of the watershed. This was supported by increased area damaged by gullies (i.e. from 480 m^2 in 2010 to 1070 m^2 in 2014). One gully head migrated 45 m up over the five years. The estimated soil loss from this gully were 299, 369, 347, 301, and 276 Mg, respectively from 2010 to 2014.

The greater sediment concentrations in catchment 2 (Figure 2 and Table III) are related to runoff contributions from an unpaved road (Guzman *et al*., in press), that is eroding a channel through the catchment (Jones *et al*., 2000). In catchment 4, sediment concentrations are elevated by an active gully/streambank failure upstream of the outlet. Because catchment 1 and 3 do not have gullies, the magnitude of sediment loads is lower compared with other nested catchments (Table III). Other studies also demonstrated that the sediment concentration is directly influenced by the presence of gullies (Bogen *et al*., 1994; Poesen *et al*., 1996; Wilson *et al*., 2008).

The reductions in peak sediment loads between 2012 and 2014 compared to 2010 and 2011 are attributed to the impacts of SWC measures implemented in the catchments. Nyssen *et al*. (2009) found a similar result in that SY has reduced by 78% following the implementation of SWC in the highlands of Tigray, Ethiopia. SCRP (2000b) also demonstrated a considerable reduction in SY (in the first five years after implementation) in Anjeni catchment, Northwestern Ethiopia. Longer-term studies however indicate that these practices become ineffective after about five years (Guzman *et al*., 2016, under review). Thus to maintain the effectiveness of SWCPs in reducing runoff and SY, maintenance is required. The Debre Mawi watershed is not an exception because most of the bunds were either half-filled or fully filled with sediment within one or two years (Figure S6), and can no longer collect runoff or trap suspended sediment. Consequently, the effectiveness of SWC measures can only be sustained if the SWCPs are maintained every one or two years or by making deeper furrows.

Peak Sediment Load Contributions in other Ethiopian Catchments and Other Countries

To see how representative the Debre Mawi findings are, the peak daily sediment loads of the Debre Mawi catchment are compared with the SCRP watersheds of the Ethiopian highlands (Table II). The contribution of peak daily loads in the Debre Mawi catchment (ranging from 23 to 73%, Table V) was greater than that of Andit Tid (9–35%) and Anjeni (5–23%), was nearly similar to that of Hundie Lafto (20–73%) and Maybar (17–79%), while the pattern in loss is the same (Figure S2). The first, two and three largest daily loads in Andit Tid catchment contributed an average of 15, 29, and 36% of the annual sediment loads. In Anjeni catchment, this was 14, 22, and 29%, in Hundie Lafto, 47, 68, and 77%, and in Maybar it was 44, 63, and 65% (Figure S2). The reasons for greater sediment loads in Debre Mawi could be attributed to variations in watershed characteristics such as soil degradation status and differences in soil texture. As shown in Table II, the soils of the steeper part of Maybar catchment are highly eroded and degraded whereas the soil degradation status is relatively lower with generally moderate soil fertility in Anjeni, Andit Tid, and Hundie Lafto. The greater contribution of early events in Hundie Lafto could be explained by the existence of Vertisols that are easily eroding and gullying (Table II) fewer storms than in the Debre Mawi watershed (Tebebu *et al*., 2015).

The contribution of 10-min event loads in the Debre Mawi catchment is larger than findings in different parts of the world. For example, Coppus & Imeson (2002) reported sediment loads of up to 15 Mg ha^{-1} for a 30-min event in a semi-arid Andean Valley. Gonzalez-Hidalgo *et al*. (2010) reported that the 25 largest events contributed more than 50% of the total load across rivers of the USA. Gonzalez-Hidalgo *et al*. (2007), based on erosion plots in the Mediterranean area, found that the three largest events produce 50% of total soil eroded. The Debre Mawi contributions are also much greater than what was reported in Gonzalez-Hidalgo *et al*. (2007), Coppus & Imeson (2002), and Lamoureux (2002) from plot scale to catchments from 110 ha to 16·7 km^2. The possible reasons for the higher sediment load patterns and differences in the magnitude of the contributions of peak loads between Debre Mawi catchment and the other studies could be related to differences in climate, topography, and status of land degradation. In a Bolivian valley (receiving 600-mm rainfall per year), midslopes have similar infiltration rates (31 mm h^{-1} vs 29 mm h^{-1}) but contain the rills and gullies (Coppus & Imeson, 2002) producing 15 Mg ha^{-1} sediment load for an extreme 30-min event whereas in Debre Mawi gullies are mostly at the lower slopes and an extreme 10-min event was capable of producing 16 Mg ha^{-1} sediment load. The Ethiopian highlands including the Debre Mawi catchment lies in the tropics, where erosive rainstorms of greater amounts fall in few months. Moreover, the Ethiopian highlands are very much degraded and often devoid of vegetation cover, which results in rapid rainfall–runoff response and severe soil erosion rates.

CONCLUSIONS

In general, a substantial proportion of the seasonal sediment transport in the Debre Mawi catchment occurs within few large runoff events. Large proportions (in most cases above 30% and a maximum of 75%) of the annual sediment loads in the catchment are transported in one or two days in a season. The 10-min peak sediment loads contributed up to 20% of the annual sediment loads or up to 12 Mg ha^{-1}. Thus, the greatest proportion of sediment is transported within few events. This indicates that considering the large amount of sediment transported during peak events is crucial in the dimensioning of hydraulic structures including SWCP. Furrows of bunds should be designed in such a way to adequately collect runoff and trap sediment transported during peak events. Increasing the depth of furrows deeper than the existing 50 cm would increase the capacity of the furrows to collect runoff and sediments as well as improve rainwater infiltration by connecting the land surface to the original deep flow paths that exist around 60 cm, and reduce runoff-induced erosion. Inclusion of gully treatment and maintenance of SWC measures are required to enhance the effectiveness of conservation measures and sustain the long-term benefits.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web site:

Supporting Information: The lists of the supporting figures provided in the text are:

Figure S1: Location of the SCRP catchments in the Ethiopian highlands.

Figure S2: Peak daily sediment load contribution to annual sediment loads for SCRP catchments.

Figure S3: The 10-min event sediment loads (Mg ha^{-1}) for the 95-ha catchment.

Figure S4: Monthly precipitation of the Debre Mawi catchment from 2010 to 2014. The "total" represents the rainfall from the beginning of June to the end of September.

Figure S5: Partial views of Debre Mawi catchment at different locations showing farming, gullies, and conservation practices

Figure S6: Furrows of bunds constructed in the Debre Mawi catchment

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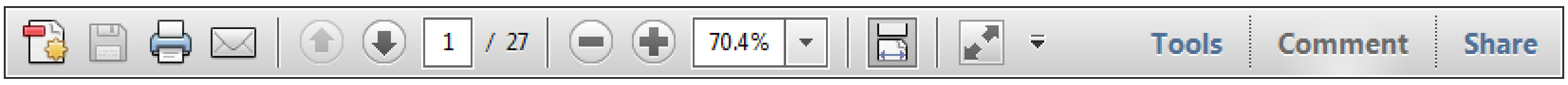

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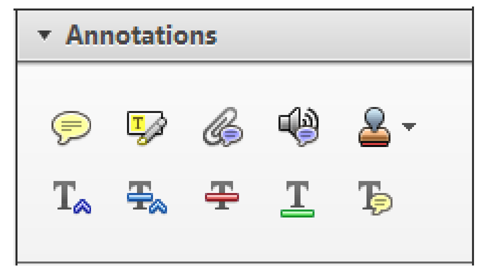

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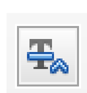

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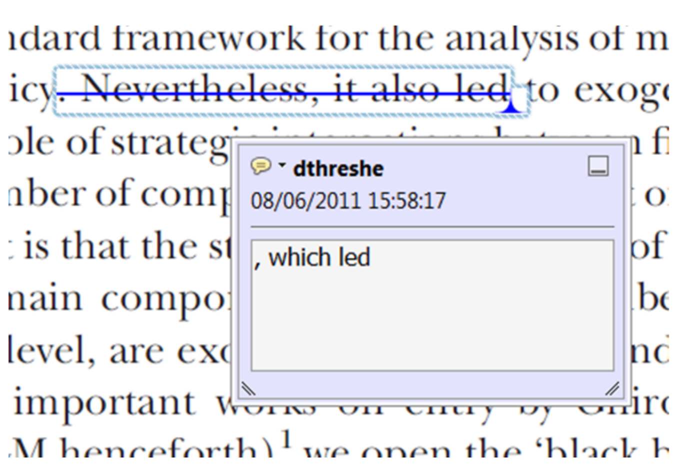

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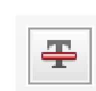

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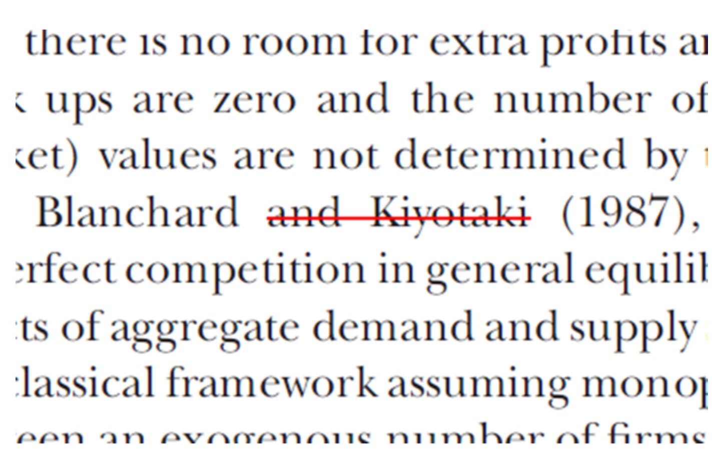

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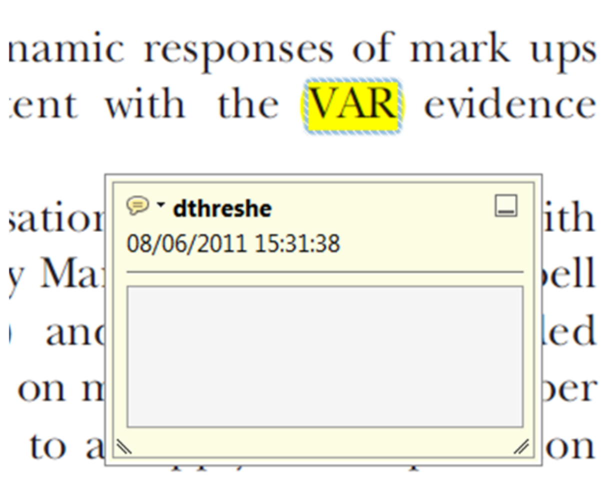

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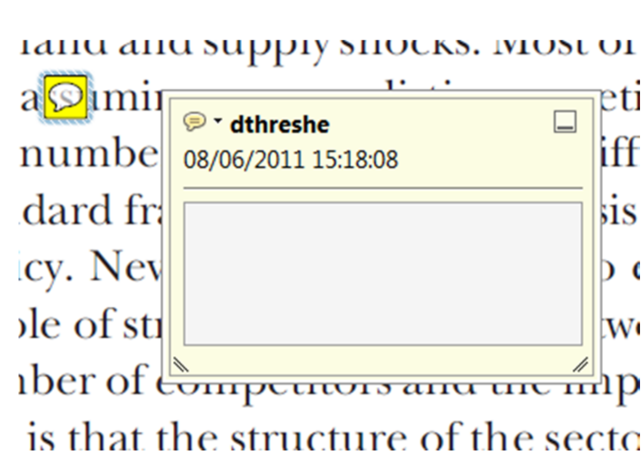

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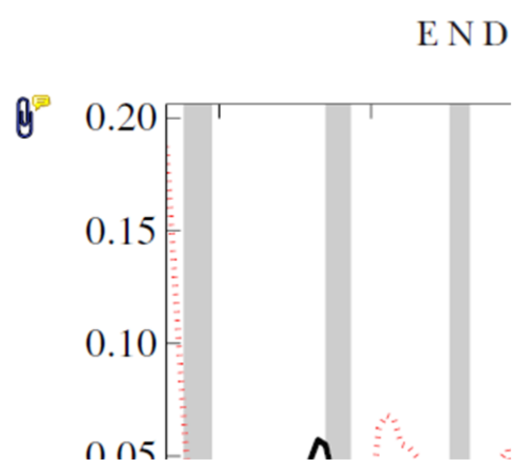
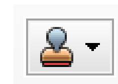
- Select the file to be attached from your computer or network.
- Select the colour and type of icon that will appear in the proof. Click OK.



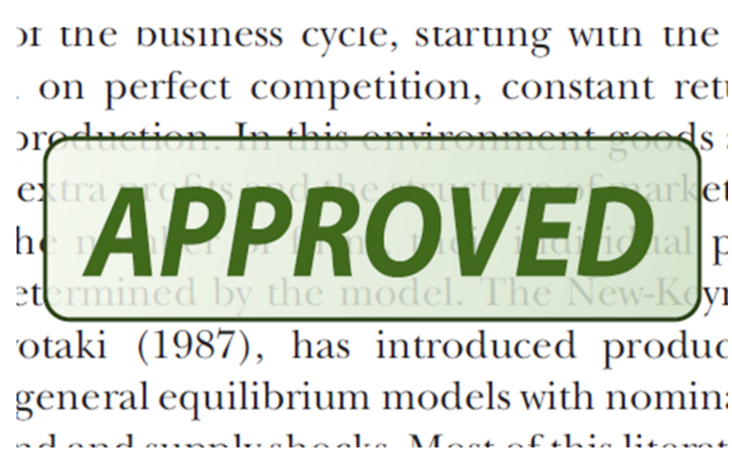
6. Add stamp Tool – for approving a proof if no corrections are required.

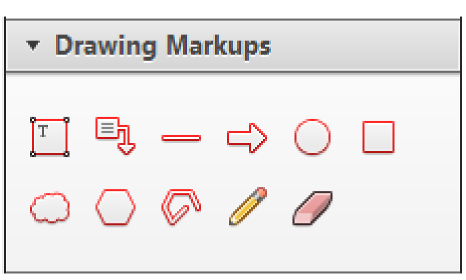


Inserts a selected stamp onto an appropriate place in the proof.

How to use it

- Click on the Add stamp icon in the Annotations section.
- Select the stamp you want to use. (The Approved stamp is usually available directly in the menu that appears).
- Click on the proof where you'd like the stamp to appear. (Where a proof is to be approved as it is, this would normally be on the first page).



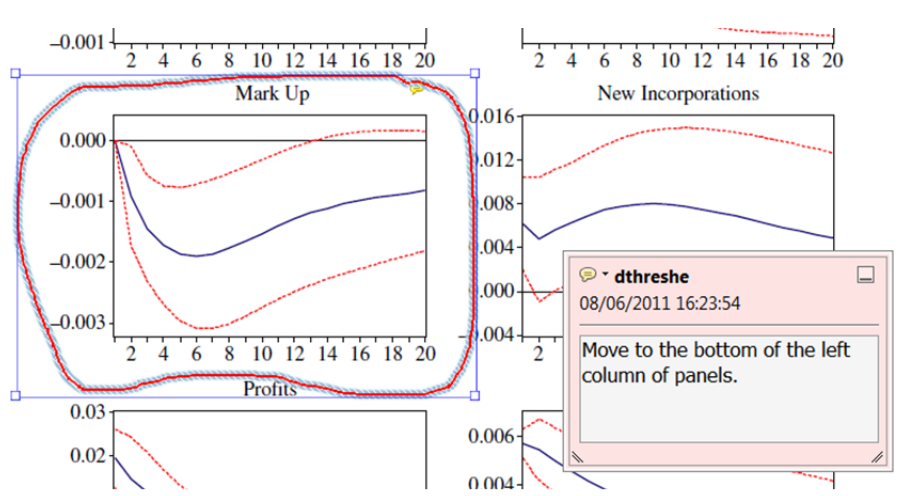


7. Drawing Markups Tools – for drawing shapes, lines and freeform annotations on proofs and commenting on these marks.

Allows shapes, lines and freeform annotations to be drawn on proofs and for comment to be made on these marks..

How to use it

- Click on one of the shapes in the Drawing Markups section.
- Click on the proof at the relevant point and draw the selected shape with the cursor.
- To add a comment to the drawn shape, move the cursor over the shape until an arrowhead appears.
- Double click on the shape and type any text in the red box that appears.



For further information on how to annotate proofs, click on the Help menu to reveal a list of further options: