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Linking soil erosion to onsite financial cost: lessons from watersheds in the Blue Nile basin

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565

Abstract

The study was conducted in three watersheds (Dapo, Meja and Mizewa) in the Ethiopian part of the Blue Nile Basin to estimate the onsite cost of soil erosion using the productivity change approach, in which crop yield reduction due to plant nutrients lost with the sediment and runoff has been analyzed. For this purpose, runoff measurement and sampling was conducted during the main rainy season of 2011 at the outlet of two to three sub watersheds in each watershed. The sediment concentration of the runoff, and nitrogen and phosphorus content of the runoff and sediment were determined. Crop response functions were developed for the two plant nutrients based on data obtained from the nearest Agricultural Research Centers. The response functions were used to estimate crop yield reduction as a result of the lost N and P assuming there is no compensation through fertilization. The results show a significant yield reduction and resultant financial loss to the farmers. Considering only grain yield of maize (*Zea mays*), farmers at Dapo annually lose about 220 and USD 150 ha⁻¹ due to the loss of nitrogen and phosphorus, respectively. In view of the importance of the crop residues including as feed, the loss can be even greater. The study demonstrated that in addition to the long-term deterioration of land quality, the annual financial loss suffered by farmers is substantial. Therefore, on farm soil and water conservation measures that are suitable in biophysical and socio-economic terms in the landscapes and beyond need to be encouraged.

1 Introduction

Soil erosion is a global environmental threat that reduces the productivity of all natural ecosystems including agriculture (Kertész, 2009; Pimentel and Burgess, 2013; Leh et al., 2013). Erosion-induced soil quality deterioration is prevalent throughout the world (Harden, 2001; Zhao et al., 2013) impeding the global food and economic security. The challenges of soil erosion are more severe in the heavily populated, under-developed,

566

and ecologically fragile areas of the world (Young, 1993; FAO and UNEP, 1999), where the adaptation capacity is weak (Cerdà, 2000; Leh et al., 2013). Tesfahunegn (2013) argues citing Lal (1981) and Eswaran et al. (2001) that misuse of soils, resulting from a desperate attempt by farmers to increase production for the growing population exacerbates soil quality degradation, and he further suggests that severity of such degradation is higher in developing countries where the economy mainly depends on agriculture. Soil erosion by water is the greatest factor limiting soil productivity and impeding agricultural enterprises in the humid tropical regions (Sunday et al., 2012). The resource-poor farmers in sub-Saharan Africa (SSA) are exposed to the pressures of soil quality deterioration the effect of which is aggravated by their limited access to the resources that are necessary to adapt.

Inappropriate land use, in which land is not used according to its suitability, and poor farming practices are the major factors leading to soil erosion induced soil quality deterioration in the highlands of Ethiopia (Erkossa et al., 2005; Angassa et al., 2014; Belay et al., 2013; Adimassu et al., 2014) and in other parts of the world (Bravo Espinosa et al., 2014), which posed socio-economic and environmental challenges. Studies conducted in northern highlands of the country show that removal of the natural vegetation for expansion of agricultural and rangeland has led to increased soil losses and growing rock outcrops, which leads to nutrient depletion and lowering of agricultural yields (Belaly et al., 2014; Woldeamlak and Stroosnijder, 2003; Mulugeta et al., 2005). Often farmers attempt to produce their traditional crops using techniques that are not necessarily suitable for the new land they access through such expansion.

Soil erosion has on-site and off-site effects. The direct on-site impact is related to agronomic productivity of plants (Lal, 1998), which is often related to nutrient loss with runoff and sediment. Hailelassie et al. (2005) estimated an annual nutrient depletion rate of 122 kg N, 13 kg P and 82 kg K ha⁻¹ from the Ethiopian highlands. Further, Adimassu et al. (2014) estimated an annual loss of 47.8 kg N, 0.60 kg P₂O₅ and 0.40 K₂O ha⁻¹ which they attributed to soil erosion alone. As a consequence of both soil erosion and nutrient depletion, more than 30 000 ha of the country's cropland

is estimated to become out of production annually (Grepperud, 1996). Quantifying the economic effects of these soil and nutrient loss, especially before the land is completely out of production remains a daunting challenge. Such information helps to substantiate investment on land management measures for the short and long term benefits to both onsite and off-site land users. Evidently, in the long-term, it is established that improved land and water management brings economic advantages to the farmer, but farmers often resist adopting such measures because they lack relevant evidence on how land degradation impacts their earnings and livelihood (Telles et al., 2013).

Availability of plant nutrients in the soil limits land and water productivity in areas where absolute quantities of water are not limiting, but even in moisture deficient areas it can be more limiting than water (Breman, 1998). Therefore, management practices that affect the nutrient content of soils directly affect farmers' income. Soil nutrient depletion is an important on-site effect of soil erosion (Bojö and Cassells, 1995; Verstraeten and Poesen, 2000). Such effects can be plausible to farmers and policy makers if expressed in terms of immediate financial cost.

According to Telles et al. (2013), the on-site costs of soil erosion can be estimated using the cost of replacement for the nutrients lost, normally macronutrients calculated on the basis of market prices for commercial fertilizers and the quantity necessary to replace the lost nutrients, plus the application cost. This approach presumes that farmers replace the lost nutrients through fertilization, which is not often the case in subsistent farming systems in developing countries. In such cases, we argue that rather the cost of not replacing the lost nutrients should be estimated and used as a proxy for the onsite cost of erosion. In line with this, Telles et al. (2013) suggest the use of estimated yield reduction as a measure of productivity loss resulting from soil limitations, including loss of the essential nutrients. The objective of this study was to quantify the essential nutrients lost due to soil erosion and to estimate the effect on the nutrient loss crop yield and household income.

2 Materials and methods

2.1 The study sites

The study was conducted in three watersheds Dapo, Meja and Mizewa with two sub watersheds for the first and three sub watersheds each for the last two, all in Blue Nile Basin (Fig. 1).

All the watersheds, except the lower part of Dapo, are situated in the highlands (above 1500 m.a.s.l.) based on the Ethiopian agro-ecological classification systems, but farmers in the districts traditionally classify the areas into high, middle and low lands. The altitude range of each traditional class was later determined using GPS handsets (Table 1). The sites receive relatively high rainfall ranging from 900 mm at Meja to over 2000 mm at Dapo, the major part of which is received during the main rainy season in summer (May–September) (Fig. 2).

2.2 Farming systems

Crop-livestock mixed agriculture is the dominant livelihood, while the major crops grown vary between and within the watersheds mainly based on altitude (Table 1). While irrigation is limited to the valley bottoms and on the sides of streams, rainfed cropping of maize (*Zea mays*), barley (*Hordium vulgare*), wheat (*Triticum aestivum*), tef (*Eragrostis tef Zucca*), and sorghum (*Sorghum bicolor*) is widespread in all the sites but potato (*Solanum tuberosum*) is also an important crop in the highland part of Jeldu. Population pressure, land degradation, inefficient use of water (rainfed and irrigated) and inappropriate land use and land and water management practices, are among the common challenges to the sustainability of the watersheds.

2.3 Runoff measurement

Runoff was measured three times a day (morning, mid-day and evening) and averaged to get a daily flow during the rainy season (which was at least 90 days) in 2011 at two

569

to three selected gauging sites in each watershed (Table 2). Discharge was measured using the Velocity-Area Method (Chitale, 1974). A current meter (*Model 0012B Surface Display Unit and Model 002 Flow Meter*) was used to measure the flow velocity (V). The flow depth at predefined cross-sections was measured using graduated wading rod (Fig. 3) simultaneously at several points spaced at varying intervals depending on the width of the stream (Fig. 4). The cross sectional area (A_i) of the flow was calculated using the flow depth (h_i) at each point. The average flow velocity at each point (V_i) and the average discharge at each sub-cross sectional area (q_i) were calculated using Eq. (1) and the total flow (Q) passing the outlet was calculated using Eq. (2).

$$q_i = V_i \cdot A_i \quad (1)$$

$$Q = \sum_{i=1}^n q_i \quad (2)$$

where:

h_i = flow depth at each cross section (m)

A_i = cross sectional area at each point (m^2)

q_i = discharge at each cross sectional area ($\text{m}^3 \text{s}^{-1}$)

V_i = flow velocity at each cross sectional area (m s^{-1})

Q = Total discharge ($\text{m}^3 \text{s}^{-1}$)

A steady-flow discharge rating curves (Fig. 5) were developed by fitting the measured gauge to discharge into power curve; water levels were measured throughout the study period using a staff gauge and the discharge was calculated from the equations of the curves (Eq. 3).

$$Q = c(H + a)^b \quad (3)$$

where:

Q = discharge ($\text{m}^3 \text{s}^{-1}$)

H = measured water level (m)

a = water level (m) corresponding to $Q = 0$

5 c = coefficients for the relationship corresponding to the station characteristics

b = coefficient for the power relation of the station characteristics

2.4 Runoff sampling and suspended sediment loss estimation

Depth integrated runoff samples were collected manually at the outlet of the sub catchments using one liter plastic bottles three times a day. The daily samples were
10 mixed and two liters were subsampled and bulked for ten consecutive days in a 20 L jerry can and kept in refrigerators at 4°C in laboratories. The suspended sediment in the bulked samples was allowed to settle and the clear water at the top was decanted into laboratory beakers. The turbid part remaining at the bottom was filtered using Whatman filter papers number 4 and oven dried and weighed. The suspended
15 sediment concentration of the runoff for each ten successive days was obtained by dividing the mass of the oven dry sediment by the volume of the runoff during the ten days interval. The decanted water and that left after filtration were mixed and subsampled for chemical analysis.

2.5 Estimates of nitrogen and phosphorus loss

20 The two essential plant nutrients, N and P content of the suspended sediment and the runoff water was determined following standard procedures for these elements (Table 2). The sum of the nutrients lost associated with the suspended sediments and dissolved in runoff was considered as the sum of these nutrients lost during the study period (Eqs. 4–6). Although rainfall started in May, discharge measurement and runoff
25 sampling was started in July, after some significant runoff had escaped, thus the total

571

nutrients loss captured during the recording period is only a fraction of what has been lost during the entire rainy season.

$$\text{Total nutrient loss (gm)} = Nu_{\text{sed}} + Nu_{\text{runoff}} \quad (4)$$

Where:

5 Nu = the plant nutrients (N and P)

Nu_{sed} = N or P lost with sediment (gm)

Nu_{runoff} = N or P lost with runoff (gm)

$$Nu_{\text{sed}} = \sum_{di=1}^n SL_{di} \cdot Con_{dis} \quad (5)$$

where:

10 SL_{di} = Soil loss during the ten days interval i (kg ha^{-1})

Con_{dis} = Nutrient concentration in sediment during the ten days interval i (gm kg^{-1})

$$Nu_{\text{runoff}} = \sum_{di=1}^n Q_{di} \cdot Con_{dir} \quad (6)$$

where:

Q_{di} = runoff ($\text{m}^3 \text{ha}^{-1}$) during the ten days interval i

15 Con_{dir} = Nutrient concentration in runoff during the ten days interval i (gm m^{-3})

2.6 Estimation of crop yield reduction

Assuming that the nutrient losses are even across the watersheds regardless of the land use and management types (Fig. 6) and further assuming that no compensation

572

through fertilization was made, as it is often the case in the areas, the yield reduction due to soil erosion was estimated using the response curves developed for the dominant crops and the two nutrients (FAO, 1999). Maize for Dapo and Mizewa, and potato and barley for Meja were considered as major crops for the assessment.

5 The response functions were developed (Table 3) based on unpublished secondary data obtained from the N and P application rates studies conducted on these crops under similar agro-ecological conditions by the nearest Agricultural Research Centers including Bako, Adet and Holeta for Dapo, Mizewa and Meja (Fig. 4), respectively.

10 The functions were used to estimate the yield that could be obtained with and without application of the nutrients lost as fertilizers and the difference between the two was taken as the net reduction in yield due to the nutrients loss. The local market price of the crops was used to convert the reduction in yield to financial loss incurred by the farmers. We obtained the farm gate price for grain and tuber from local markets and the average price (ETB 100 kg⁻¹) was 350 for maize and potato and 500 for barley,

15 where the average exchange rate in February 2012 (USD 1 = ETB 19.89) was used for conversion.

3 Results and discussion

3.1 Runoff and sediment load

20 The total runoff per hectare during the season was highly variable between and within the sites, although there was minor difference in terms of the rainfall received during the same period (Table 4). On average, the highest runoff volume was from Mizewa while the least was from Dapo, which is comparable with that from Meja.

The runoff from the watersheds and the sub-watersheds seems to have been influenced by factors such as topographic characteristics, land use and management practices implemented (Hartanto et al., 2003; Gary and Carmen, 2007). For instance,

25 runoff from Kollu sub-catchment at Meja was 135 times higher than that from Gallessa.

573

A large proportion of Gallessa is flat and waterlogged, and a major part is used for grazing or cultivation of potatoes that are often planted early in the season on contours, to cover the land during the peak season, thus increasing water infiltration. In contrast, Kollu is characterized by steep slopes and largely cultivated to cereals that are planted

5 late in the season exposing bare land to erosive force of rainfall and runoff. Therefore, improving land use and management practices, such as growing permanent crops on the steep slopes (Hartanto et al., 2003), contour cultivation (Quinton and Catt, 2004) and early planting to ensure sufficient land cover during the peak rainfall season and implementing soil conservation practices such as soil bunds stabilized with vegetative

10 materials may allow more infiltration (Cerdà, 1998) of water that can be used by the crops during the dry season and reduce loss of soil and water.

3.2 Suspended sediment export

The average sediment lost during the study period ranged from 2334 kg ha⁻¹ at Meja to 5689 kg ha⁻¹ at Dapo (Fig. 5), and this is lower than most estimates for the Ethiopian

15 highlands where the estimated annual soil erosion rates range from as low as 16 t ha⁻¹ (Gizawchew, 1995) to as high as 300 t ha⁻¹ (Hurni, 1993; Herweg and Stillhardt, 1999). As discussed earlier, in all the sites, rainfall started in May, but runoff measurement and sampling began in early July after the most sensitive time in terms of soil erosion has passed. At all the sites, intensive tillage for land preparation which keeps the soil

20 surface bare and vulnerable to the detaching forces of raindrops and runoff starts in April and May depending on the onset of rainfall. Therefore, the sediment loss reported here is only a portion of the total loss. For instance, a modeling effort for the same year using RUSLE revealed an estimated annual soil loss rate of 10, 4 and 5 t ha⁻¹ for lower Mizewa, upper Mizewa and Gindenewur sub-catchments, respectively (Getnet et al.,

25 2013). In addition, not all the sediment that is lost from the upstream fields is delivered to the outlet since part of it is deposited on its way (Pathak et al., 2004). Consequently, the data may not show the full picture and should be interpreted only in relative terms.

574

In contrast to its lowest runoff, Dapo exhibited the highest sediment loss per unit area during the study period. This may be related to the high rate of active deforestation that exposes topsoil on sloping land to the detaching forces of raindrops and the high transport capacity of runoff created by the steep slope gradient. This is particularly true for Chekorsa sub-catchment in which the peak sediment concentration coincided with the peak runoff (Wudneh et al., 2014). Mizewa revealed lower soil loss than Dapo, despite its highest cumulative runoff. According to Pathak et al. (2004), several factors such as storm size, duration and intensity, changes in crop canopy during the season, tillage timing, and changes in grass waterway conditions explain the major parts of the variation in sediment concentration among the sub-watersheds. In addition, the lower soil loss from Mizewa can partly be attributed to a longer history of its exposure to accelerated soil erosion which might have led to armoring effect due to the selective soil erosion by water (Charles and Black, 2001), in which case detachment instead of transportation would be the limiting factor.

3.3 Nitrogen and phosphorus export

The buildup and depletion, respectively, of plant nutrients from agricultural soil has become a major environmental problem in developed and developing countries. Soil erosion and leaching are among the major factors responsible for nutrient depletion from agricultural lands in humid tropical areas in Africa (Henao and Baanante, 1999). The rate of nitrogen and phosphorus loss due to erosion is often related to the rate of runoff and soil erosion (Wu et al., 2012). This study revealed that N and P loss was strongly related to the soil loss in which, the highest N (14 kg ha^{-1}) and P (6.8 kg ha^{-1}) was from Dapo where the sediment loss was the highest. However, while the sediment loss at Dapo was 2.3 times higher than that from Mizewa (the lowest), the N and P loss was even higher (6.7 and 3.6) times, respectively compared to that from Mizewa. In part, this may be related to the fact that Dapo is experiencing active expansion of agriculture to forested areas that are rich in these nutrients. Therefore, limiting land

use change from forest to agriculture by intensifying productivity in areas already under cultivation may mitigate the loss of sediment and nutrients.

3.4 Effect of N and P loss on crop yield

The impact of soil erosion on the productive potential of agricultural lands is well known (Pathak et al., 2004), but the magnitude depends on local circumstances. In the study areas, the loss of the essential plant nutrients N and P in association with the suspended sediments and runoff during the measurement period and the attendant yield and income losses suffered by farmers were remarkable. Predictably, the maximum yield reduction and resultant financial loss due to the two plant nutrients considered was from Dapo (Table 4) which corresponds to the highest loss of these nutrients while the least was from Meja. Compared to Meja, the estimated yield reduction due to N and P loss from Dapo was 11 and 7 times higher while the corresponding financial loss was 7 and 5 times higher, respectively. The relatively lower financial loss is related to the lower market price of maize that is grown at Dapo as compared to barley and potato, which are dominant at Meja.

In addition to the reduction in crop yield that directly affects the land user, both N and P contribute to eutrophication of freshwater bodies that are important for various ecosystem services (Conley et al., 2009; Lewis et al., 2011), affecting the society at large. Consequently, maintaining or improving water quality in lakes, ponds etc. that may experience man-made eutrophication requires reducing inputs of both nutrients to the water bodies, especially from agricultural lands, where these nutrients are needed by crops in large quantities. Therefore, although controlling runoff and soil erosion should be done on farm lands, farmers need some incentives in addition to reducing yield loss. Other stakeholders that benefit from the avoided risk of damage to the ecosystem services such as maintaining the quality of water need to support them through various frameworks such as payment for environmental services, which requires establishment of upstream and downstream institutional linkages.

4 Discussions

The measurement and sampling of runoff for sediment and nutrient loss estimation was only for part of the season since it was started late. Essentially, the rate of soil loss is generally higher during the early part of the rainy season since this is the time when farm operations are intensive and the soils remain bare. This implies that a substantial part of the sediment loss was not captured by this study. Besides, the other macro and micro nutrients have not been considered, thus the study explained only part of the problem. Soil erosion also brings about a loss of soil quality (Blaschke et al., 2000) including its physical deterioration, which has repercussions both on its nutrient and water holding capacity and thereby on productivity.

Despite this apparent under estimation of the impact, compared to the average income of the subsistent farmers (USD 60 ha⁻¹) (IFPRI, 2010), the estimated yield reduction and loss of income due to the loss of the two essential nutrients can be considered high, regardless of the location considered. The estimate presumes no substitution of the nutrients either through external inputs or internal regeneration. The use of technologies for compensating the nutrients such as applying more nutrients and using management practices increases production costs and reduces net farm income. However, using soil and water conservation practices that control erosion, these costs can be minimized, which improves the sustainability of the agriculture sector (Lal, 2006; Montgomery, 2007). Soil loss and attendant nutrient removal were highest at Dapo where more new land is being put under cultivation, and lowest from Mizewa, an area that has been under cultivation for a relatively longer time. This suggests that soil conservation control efforts should be prioritized in areas with high soil and nutrient loss potential so that their productivity is maintained.

In such areas, however, farmers may not feel the effect in the short term, and thus often resist using conservation practices as they believe exploiting the stock of natural fertility is an adequate solution as long as earnings are higher than production costs. In the long term, this may lead to exhaustion of the soils, making agricultural activities

economically unsustainable (Telles et al., 2013). Convincing the land users of the need for action against land degradation requires that the net benefit from implementing conservation practices be clearly established. This needs to take into account the inputs required, including labor and the negative impacts of some measures such as land taken out of production due to soil or stone bunds that are often necessary for erosion control. Although there is often a strong justification for households to implement improved land and water management practices on their farms even without external support, since the society at large can also be a victim of no action, farmers need to be encouraged through various incentives to take measures. While the benefits from some improved management practices may be realized in the long-term, approaches that increase income even in the short term need to be explored, based on the comparative advantage of the sites. This study demonstrated that soil erosion can cause immediate damage to the financial income of the households. Policy makers and the local extension system can use this evidence to substantiate the need for immediate interventions and convince the land users to engage in efforts to minimize soil and nutrient losses. This could also be an input to the linkage between upstream and downstream land and water users to avoid the negative impacts on ecosystem services.

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Table 1. Major characteristics of the study watersheds.

Watershed name	Landscape position	Altitude range (m a.s.l)	Mean annual rainfall (mm)	Major crops	Major challenges
Dapo	Upper	Higher than 2000	1376–2037	tef, finger millet, niger seed, sorghum, maize, sorghum, sesame, finger millet, maize, sorghum, sesame, finger millet	demographic pressure, deforestation, overgrazing, soil erosion, soil fertility depletion, termites, water and land scarcity, inefficient irrigation scheme, lack of water storage systems, high rate of deforestation, soil acidity
	Middle	1451–2000			
	Lower	Less than 1450			
Mizewa	Upper	2000–2200	974–1516	barley, tef, faba bean, maize, finger millet, tef rice	shallow water table (2–4 m), flooding, water logging, upper and middle: shallow and stony soils, bottom part: water shortage
	Middle	1800–2000			
	Lower	1785–1800			
Meja	Upper	2700–3200	900–1350	potato, wheat, barley, wheat, tef, sorghum, maize, tef, sorghum	inefficient irrigation practice: – 60 % delivery loss – water application is by wild flooding deforestation, cultivation of steep slopes, soil erosion, plant nutrient depletion, shallow soil depth
	Middle	2300–2700			
	Lower	1800–2300			

Source: Offices of Agriculture, Annual Reports (2006 to 2010); ILRI Baseline Survey Report, 2010 and own survey

Table 2. Methods and procedures used for the chemical analysis of sediment and water samples.

Sample	Parameter	Method	Reference
Sediment	NO ₃ -N and NH ₄ -N	Magnesium Oxide-Devrda's alloy	Maiti (2004)
	Phosphorus	Olsen	Olsen et al. (1982)
Water	Dissolved NH ₄ -N	Phenate method using Spectrophotometer	Patnaik (2010)
	Dissolved NO ₃ -N and phosphorus	Spectrophotometer	Patnaik (2010)

Table 3. Response equations of the selected crops to N and P application rates.

Location	Crop type	Response to N Equation	R^2	Response to P Equation	R^2
Dapo	Maize	$Y = -0.22N^2 + 72.75N + 2483$	0.72	$Y = -1.1(P_2O_5)^2 + 162.7P_2O_5 + 2483$	0.72
Mizewa	Maize	$Y = -0.29N^2 + 58.6N + 2537$	0.75	$Y = -0.55(P_2O_5)^2 + 82.25P_2O_5 + 2691$	0.88
Meja	Potato	$Y = -0.001N^2 + 0.309N + 16.15$	0.71	$Y = 0.005P^2 + 0.6465P + 16.54$	0.90
	Barley	$Y = -0.412N^2 + 39.94N + 1129$	0.89	$Y = -0.516P^2 + 53.33P + 1209$	0.77

Y stands for grain or tuber yield (kg ha^{-1}), N and P stand for nitrogen and phosphorus application rates (kg ha^{-1}).

Table 4. Average runoff and sediment loss during the season from the catchments.

Catchment	Sub catchment	Area (ha)	Runoff ($\text{m}^3 \text{ ha}^{-1}$)	Sediment loss during the season (kg ha^{-1})
Dapo	Dapo	1620	3196	4072
	Chekorsa	560	3900	7306
	Average		3548	5689
Mizewa	Lower Mizewa	2664	6885	3173
	Upper Mizewa	1870	6882	1599
	Gindenewur	715	6882	2520
	Average		6883	2431
Meja	Melka	9200	2707	2675
	Kollu	250	8079	1847
	Galessa	160	60	2481
	Average		3615	2334

Table 5. Nitrogen and phosphorus export with suspended sediment and dissolved in runoff during the season from the sub catchments.

Catchment	Sub catchment	Nutrient loss (kg ha ⁻¹)		Estimated yield loss (kg ha ⁻¹) due to		Crop type	Financial loss (USD ha ⁻¹ year ⁻¹) [*]	
		N	P	N	P		N	P
Dapo	Dapo	13.6	9.3	949	1421	Maize	171	263
	Chekorsa	14.3	4.2	1013	664		188	123
	Average	14.0	6.8	981	1043		179	193
Mizewa	Lower Mizewa	2.3	1.8	134	320	Maize	58	138
	Upper Mizewa	1.6	1.8	93	328		40	142
	Gindenewur	2.3	2.1	134	382		58	165
	Average	2.1	1.9	120	343		52	148
Meja	Melka	9.0	6.0	32	47	Barley	13	19
	Kollu	17	5.0	25	43	Potato	10	17
	Galessa	3.0	3.0	210	340		50	81
	Average	9.7	4.7	89.0	143	24	39	

^{*} Average exchange rate in February 2012 was USD 1 = ETB 19.89.

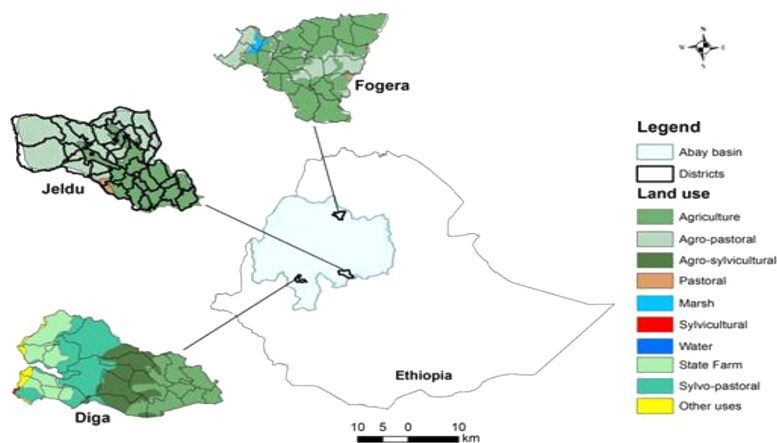


Figure 1. Location of the study sites.

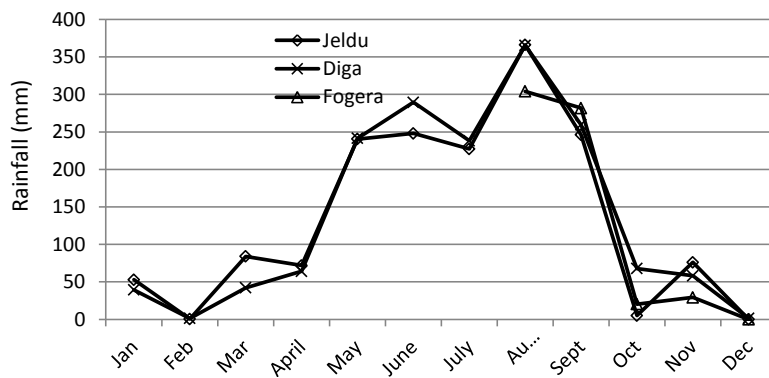
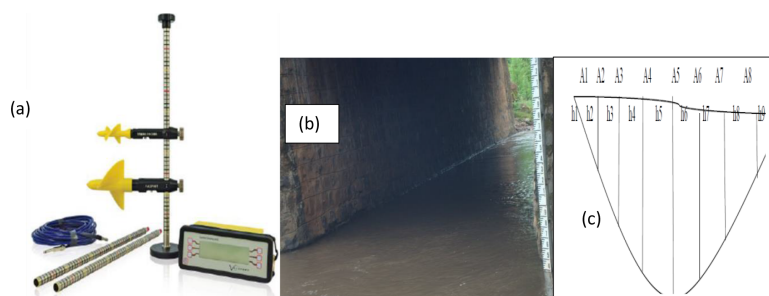


Figure 2. Rainfall of the study sites in 2011.



Source: Wudneh et al. (2014)

Figure 3. Current meter (a) used for measuring river flow and staff gauge (b) cross section and sub-cross sectional areas where flow velocities were measured (c).

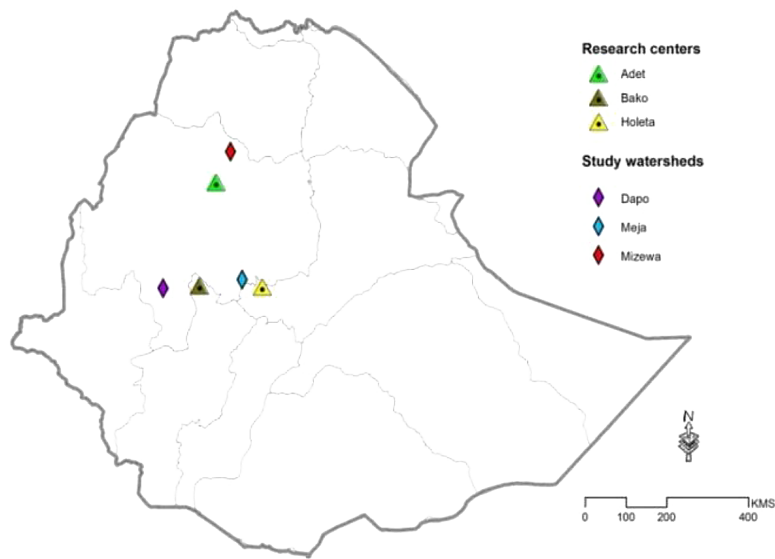


Figure 4. Location of the research centers close to the watershed sites.

591

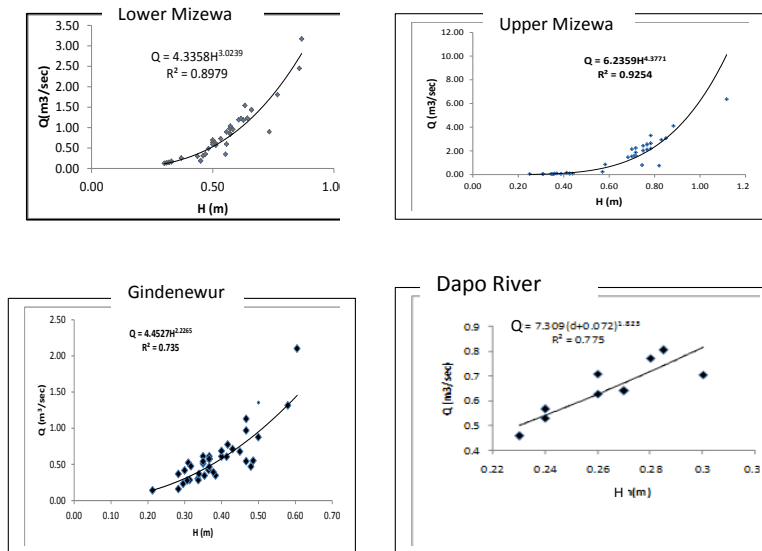


Figure 5. Discharge rating curve for some of the sub watersheds.

592

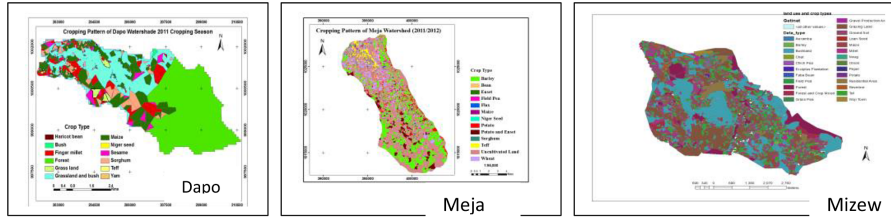


Figure 6. Crop pattern maps of the study watersheds during period (2011).

593

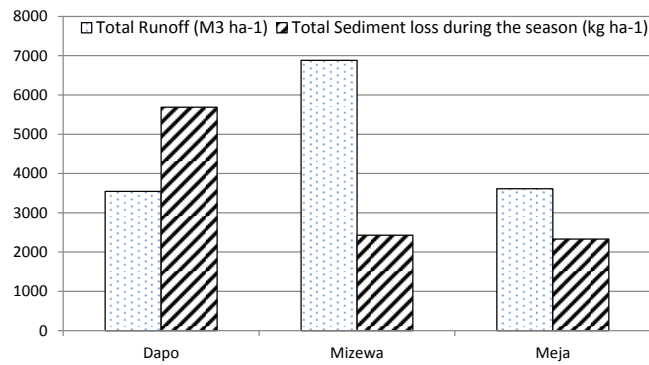


Figure 7. Average runoff and sediment loss during the measurement period at the study sites.

594