Evaluating the Role of Runoff and Soil Erosion on Nutrient Loss in the Chenetale Watershed, Upper Blue Nile Basin, Ethiopia

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Abstract. The non-point source pollution of agricultural nutrients (P and N) by surface water is not well quantified in the Ethiopia highlands. The objective of this study was to quantify soil nutrients (N and P) from an agricultural uplands area in upper Blue Nile basin. A small watershed (104.6 ha) and nested gully catchment were gauged for data collection. Two years (2015 and 2016) data of runoff, sediment, sediment-associated and dissolved soil nutrients loss were collected from two gagging stations. Both dissolved and sediment associated nutrients were computed for 2015 and 2016 rainy seasons. The result indicated that sediment associated nutrient loss was significantly higher than the dissolved nutrient loss. In 2015, the nutrients loss was 8.93 kg $ha^{-1}yr^{-1}$ N and 0.3 kg $ha^{-1}yr^{-1}$ P at the outlet of W-1 and 3.04 kg $ha^{-1}yr^{-1}$ N and 0.14 kg $ha^{-1}yr^{-1}$ P at the outlet of W-2. In 2016, 7.67 kg $ha^{-1}yr^{-1}$ N and 0.24 kg $ha^{-1}yr^{-1}$ P were lost at the outlet of W-1 and 8.44 kg $ha^{-1}yr^{-1}$ N and 0.57 kg $ha^{-1}yr^{-1}$ P were lost at the outlet of W-2. Nutrients losses with sediment were 91.3% and 45.6% of N and P, respectively. High amount of nitrogen was lost with sediment than in dissolved form indicating that soil erosion is an important process for soil nutrients losses in the highland. Therefore, soil and water conservation practices are practically significant to control soil nutrients loss.

Keywords: Nutrient loss · Runoff · Erosion · Ethiopia

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1 Introduction

The transport of nutrient from agricultural watersheds has been a worldwide environmental concern due to its sensitivity to reduce productivity and surface water pollution [1]. Nutrients carried with surface runoff and eroded sediment can accelerate the eutrophication in lakes and ponds [2]. The primary surface-water pollutants from agricultural lands are sediments, nutrients and herbicides, which need the management practices to minimize their losses from agricultural watersheds [3–5]. Various studies in the globe have provided critical analysis of the processes involved in the release, transport, and biological availability of soil nutrient [6, 7], and the specific impacts of agricultural nutrients on surface water bodies [8–12].

Agriculture is the major source of livelihood for more than 80% of Ethiopian population [13]. However, the agricultural sector, the major livelihood source of farmers, is under continuous threat from the effects of land degradation mainly caused by water-related soil erosion and soil nutrient depletion [14–17]. Land degradation in the Ethiopian highlands has been one of the most prominent problems for the last few decades. Ethiopia has been described as one of the most serious soil erosion prone areas in the world [18]. But it is important to consider further the impact of runoff and erosion on nutrient losses.

The non-point source pollution of agricultural nutrients (P and N) by surface water are not well quantified in the Ethiopian highlands [3]. Only few studies have been conducted on role of soil erosion to nutrient loss in Ethiopia [19–21]. Nutrient losses from agricultural land also imply an economic loss to the farmer by both reduction of crop yield and increasing the replacement cost of soil nutrients [22]. Moreover, nutrient losses can also contribute to water pollution in downstream water bodies [23].

Given the severity of land degradation in Ethiopia, government and development organizations invested huge amount of resources to combat the soil erosion problem [24, 25]. Promotion of sustainable land management (SLM) technologies such as soil bunds has been suggested as a key strategy to reduce land degradation and increase crop production [15]. As stated by [26] “One of the main issues facing the establishment of effective non-point source management controls is the development of economically and environmentally sound P and N management systems and the balancing of productivity with environmental values”. Not surprisingly, the problems are most severe in areas where water movement from soil to surface water is greatest and where soil P and N levels are highest.

This paper therefore, has quantified the nutrient loss from soil erosion and runoff in the upland agricultural watershed of the upper Blue Nile Basin, Ethiopia. Such as assessment of relative contribution of nutrient from soil loss and runoff is of critical importance to prevent environmental pollution and helps to formulate appropriate type of conservation practices in the Ethiopian highlands.

2 Materials and Methods

2.1 Description of Study Area

Chenetale watershed is located in the Ethiopian high lands, in the Blue Nile Basin. It is about 140 km from Bahir Dar to South, in Guagussa-Shigudad Woreda, in Awi Zone, and 10 km from the Woreda capital Tillile. The climatic condition of the watershed is sub-humid and the elevation ranges from 2200 to 2700 meters above sea level. As shown in Fig. 1, the watershed lies between 10º 79′76″ and 10º 78′29″ North and 37º 05′59″ and 37º 06′74″ East. It receives annual rainfall between 1400 mm and 1700 mm. The average minimum and maximum annual temperature vary between 18 °C and 25 °C. The upper part of the watershed is steeper slope which is about 57% while the bottom part of the watershed towards the outlet is gentle slope and about 3%. The total area of the watershed covers about 483.6 ha; only 104.6 ha of the watershed

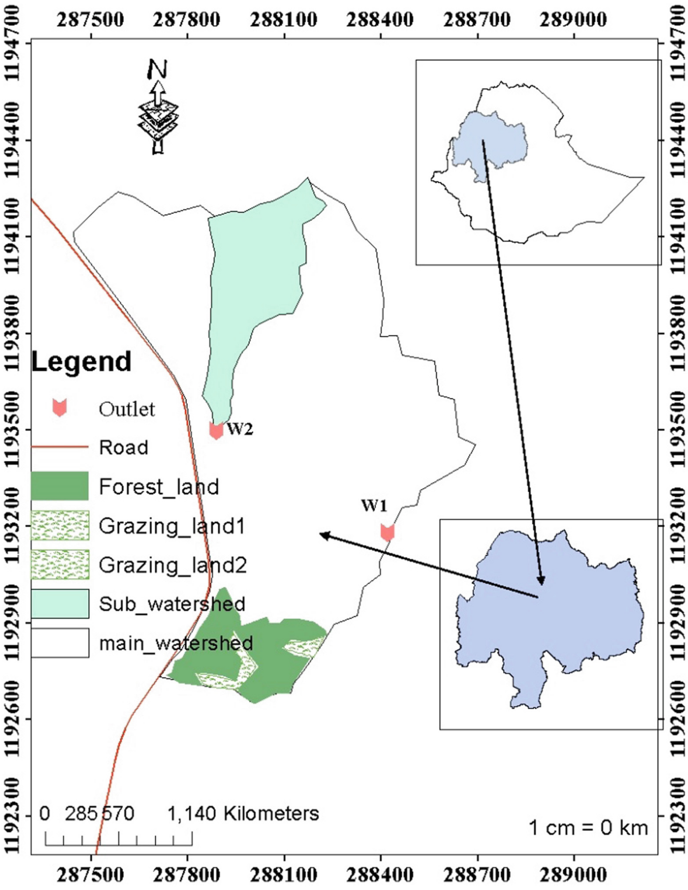

Fig. 1. Location map of study area

is selected for the experimental design. The area is characterized by intensive agriculture with an average land holding of 0.65 hectares per household.

The watershed is dominated by cultivated land. The most common type of crop is wheat, pea, bean, barley and teff. The major part of the study area (91%) is crop land and small part is covered with forest (juniper tree) (8%) and the remaining is covered with grazing (1%) in the main watershed (Fig. 1). The soils in the watershed are classified as Nitosols and Vertic-Nitosols. Nitosols which are found in the upper part of the watershed is rich in deep red clay soil. The Vertic-Nitosols also located in down part of the watershed near to the outlet. It is reddish-brown which has a capability to drain and hold water when it gets wet and dry, respectively. It is mostly suitable for teff crop.

2.2 Data and Methodology

Hydro-Meteorological Data. Rainfall and flow measurement were carried out in 2015 and 2016 rainy seasons. One manual plastic rain gauge was installed to collect rainfall data. Rain fall data was collected from June to November 2015 and from May to October 2016. The missed data of May 2015 and early May 2016 were taken from the Bure meteorological station which is 6 km away from the watershed to the south. The rainfall data of Bure meteorological station was collected from the Bahir Dar national meteorological station (Fig. 2).

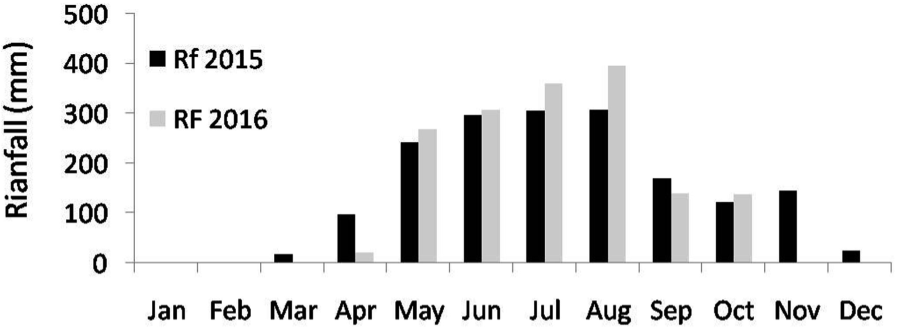

Fig. 2. Monthly rainfall distribution

Two stone masonry weirs were constructed to measure stream flow at the outlets. Weir-1 (W-1) was installed at the outlet of the watershed and weir 2 (W-2) was installed at the outlet of a gully as nested watershed. In 2015 rainy season, flow depth and surface velocity of the runoff using a floating method were collected in 20 min intervals during storm runoff. In 2016 rainy period, the runoff data at W-2 were collected at every 15 min interval but at W-1 measuring interval was continued as 20 min. The change in W-2 was due to the small size of the catchment and to capture all peaks. Surface velocity was measured by dropping a floater at 15 m upstream of the weir and the travel time to reach the weir was recorded using hand watch. The calculated flow velocity at the surface was multiplied by two-third to get average velocity [27]. The flow rate was calculated by multiplying the mean velocity with cross sectional area of the weir at measured depth. Rating curve was developed for each weir from the scatter plotting of depth vs. discharge (Figs. 3 and 4). A power function was as shown in Figs. 3 and 4. The daily average runoff depth was computed by dividing total discharge in the day by contributing area of the watershed.

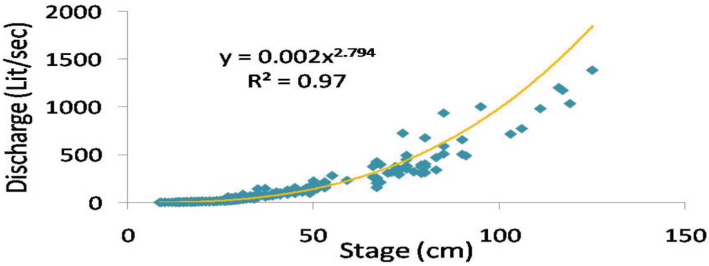

Fig. 3. Stage discharge relationship at weir 1

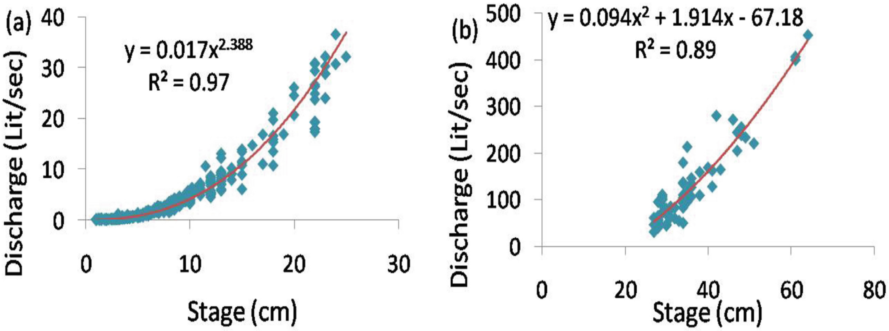

Fig. 4. Stage-discharge relationship at weir 2 (x in the equation indicated the depth of flow in the weir, a, x <= 25 cm and b, x > 25 cm)

Sediment concentration was computed from 1 L of sample collected at weirs (W-1 and W-2) during storm runoff events in 2015 and 2016. The sampling periods were from June 27, 2015 to November 21, 2015 and from May 21, 2016 to October 14, 2016, when there was the surface runoff. From the collected runoff water samples the suspended sediment was estimated by using gravimetric method. The instant sediment yield was calculated by multiplying sediment concentration with calibrated discharge and summed up over the season to estimate the total loss from the watershed.

Nutrient Loss. Atotal of 104 and 105 runoff water and sediment samples were collected in 2015 and 2016, respectively to analyze the nutrients loss by erosion. Filtered water samples from each storm events were composited and samples of 100 ml were collected and preserved by 2 ml of HCL until the collected samples are analyzed at Bahir Dar University, Bahir Dar Technology Institute, Hydrology Laboratory. From the samples dissolved phosphorous (P) and dissolved nitrogen (N) were analyzed using palintest photometer. The total nutrient lost from the watershed was computed by multiplying the nutrient concentration with total instant discharge. The Palintest Nitratest method provided a simple test for nitrate nitrogen within the threshold level of 1 mg/l N and the Palintest Phosphate LR test also measure phosphate levels within the threshold limit of 1.3 mg/l P. The test was however be extended to analyze the nutrient concentration of the sample over the threshold range of the palintest by a simple dilution technique. The diluted concentration of the sample read from the photometer was multiplied by the dilution factor to get the original concentration.

For sediment associated nutrients (N and P) analysis, sediment from two weeks filtered storms runoff samples were composited to meet the minimum requirement of sample size for analysis. The samples were analyzed at Amhara Design and Supervision Works soil laboratory for particulate nutrient lost.

Kjeldahl method was used to determine total nitrogen associated with particulates [28]. The phosphorus concentration was determined using Olsen et al. method [29]. Thus, total soil nutrient lost was the sum of dissolved and sediment-associated laboratory results. The nutrient losses were calculated as following:

$$\text{Nutrient loss (kg)} = \text{concentration of nutrients lost}\ \left(\text{mg l}^{-1}\right) \times \text{runoff}\ \left(\text{m}^3\right) \times 10^3 \tag{1}$$

$$\text{Available Phosphorus (Av.P) loss (kg)} = \text{Sediment yield (kg)} \times \text{Av.P (ppm)} \times 10^{-6} \tag{2}$$

$$\text{Total Nitrogen (TN) loss (kg)} = \text{Sediment yield (kg)} \times (\text{TN}\ (\%)/100) \tag{3}$$

3 Result and Discussion

3.1 Runoff

A total of 213 mm and 268 mm runoff from W-1 and 102 mm and 229 mm runoff from W-2 were recorded in the 2015 and 2016 rainy phases, respectively. The runoff generated from the rainfall was low at the beginning of the rainy season and increased in August. To compare runoff among the sub-watersheds, a runoff coefficient (the quotient of runoff to rainfall volume) was calculated for each month that data was available for each outlet. June had the lowest runoff coefficient in 2016 indicated that most of the rainfall was infiltrated. The increasing trend of runoff coefficient from June to September was observed. The runoff coefficient at W-1 for the month of September was 0.27 in 2015 and 0.4 in 2016. Greater runoff coefficient in 2016 was because of the higher rainfall amount in the season. The runoff coefficient at the outlet of W-1 was higher than the runoff coefficient at the outlet of W-2 in 2015 because higher fraction of rainfall was infiltrated at the upper part of the watershed and contributed by subsurface flow. The difference in runoff coefficients between the two recording years was that the rainfall in 2015 was relatively small in magnitude and uniformly distribute through the year while the rainfall in 2016 was concentrated during the rainy season (Fig. 5).

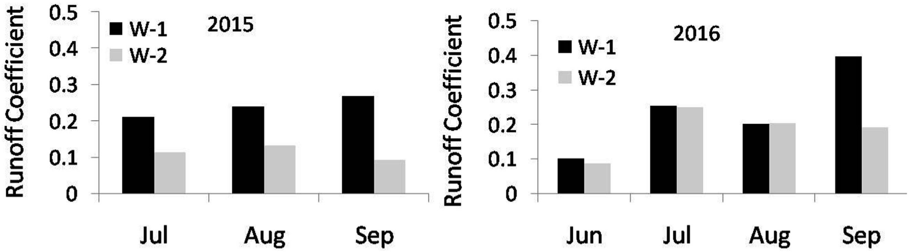

Fig. 5. Runoff coefficients at the outlets in 2015 and 2016

3.2 Sediment Concentration and Load at the Two Gauging Weirs

The sediment concentration and load of the two weirs were monitored at the gauging weirs during two consecutive rainy seasons. it was observed that the sediment concentration from the storm runoff was higher than the sediment concentration during the non-rainy time. This was because of the dilution from base flow. The sediment concentration from storm runoff was very slightly higher in August at the outlet of W-1 and in July at the outlet of W-2 in 2015. In 2016 rainy season, the sediment concentration was higher in July at both gauging stations (Fig. 6). Most of the time high sediment concentration was observed in the month of July. This could be most likely due to the peak agricultural practices and difference in distribution and amount of rainfall in the two rainfall years.

The total sediment lost from whole watershed and nested gully catchment in 2015 was 6.43-ton ha^{-1} yr^{-1} and 2-ton ha^{-1} yr^{-1}, respectively and in 2016, it was 7-ton $ha^{-1}yr^{-1}$ and 9-ton ha^{-1} yr^{-1}, respectively. Less sediment yield and concentration at W-1 than W-2 in 2016 indicated that high rainfall likely raised the perched groundwater table and as a result increased the slumping of gully banks and gullies become source of sediment [30].

3.3 Dissolved Nutrients Loss

The research results indicated that average concentration of dissolved nutrients at the outlet of sub watershed and nested watershed (gully catchment) in 2015 was 1.49 mg l^{-1} and 1 mg l^{-1} N, and 0.272 mg l^{-1} and 0.31 mg l^{-1} P, respectively. In 2016, the average concentration of dissolved N and P was 2.34 and 0.25 mg l^{-1} at the outlet of the sub watershed and 1.61 and 0.62 mg l^{-1} at the nested watershed, respectively. The figures indicated that the difference in the concentration among the experimental watersheds was not significant for P but significant for N in 2015. Nevertheless, there is significantly higher difference among the watersheds for P concentration and vice-versa for N in 2016 (Table 1). This indicated that the highest accumulation of clay has strong relation with P because of the preferential loss of P with finer clay sized particle. High concentration of nutrients lost was significant in low depth and long duration of rainfall and runoff (See Fig. 7).

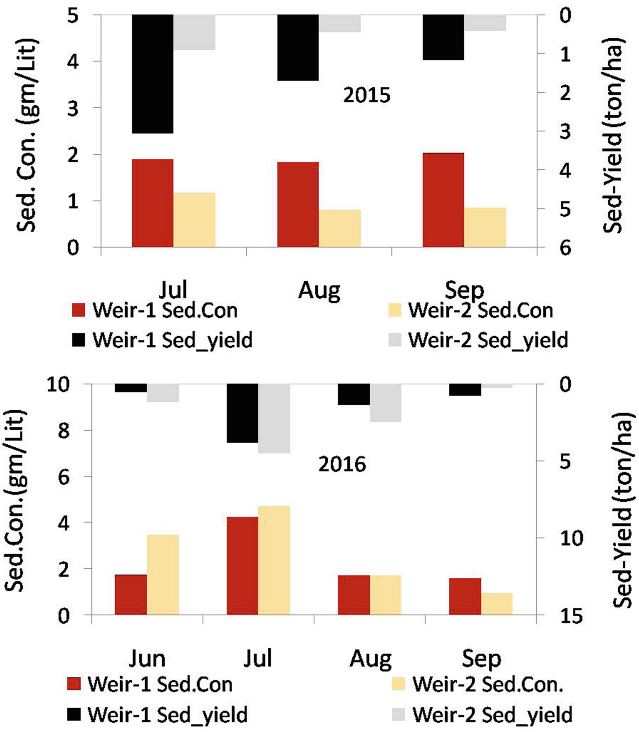

Fig. 6. Monthly sediment yield and average sediment concentration at the gauging outlets in 2015 and 2016

Table 1. Statistical test (ANOVA single factor) at 5% significance level was carried out to compare the nutrients concentration among the watersheds.

Variables	P-value between watersheds	
	2015	2016
N	0.005	0.146
P	0.436	0.0027

The monthly dissolved nutrient losses in experimental watersheds showed that dissolved nutrient losses were low at the beginning of the rainy season and increased progressively throughout the rainy season (Fig. 8). Nutrient transport with in runoff tends to increase with increasing runoff. The total dissolved nutrients lost from W-1 and W-2 in 2015 monsoon period was 0.5 and 0.34 kg $ha^{-1}yr^{-1}$ N, and 0.14 and 0.09 kg $ha^{-1}yr^{-1}$ P, respectively. The amount of nutrients lost from the experimental catchments during 2016 rainy season was estimated, about 0.67 and 0.94 kg $ha^{-1}yr^{-1}$ of N, and 0.08 and 0.37 kg $ha^{-1}yr^{-1}$ of P from W-1 and W-2, respectively. The result of nutrients analysis from storm runoff leaving the study watershed indicated that

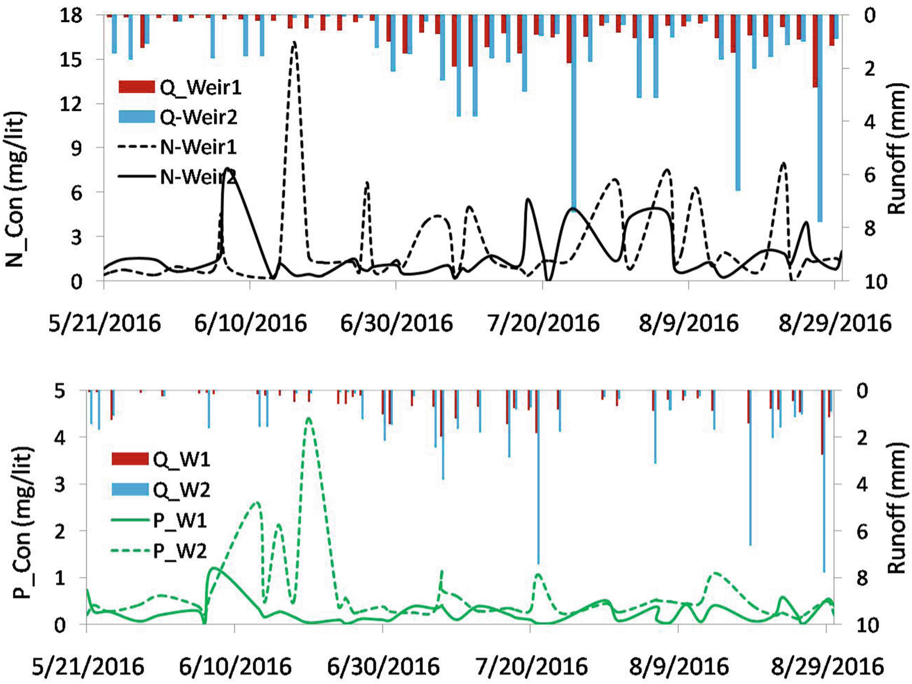

Fig. 7. Temporal distribution of dissolved nutrient concentration and runoff depth in 2016 rainy season

surface runoff is an important component to export dissolved nutrients from agricultural watersheds and runoff should be considered while developing management strategies to minimize nutrients loss from the agricultural lands (Table 2).

3.4 Sediment Associated Nutrients Loss

The analyses of total soil nutrients loss from the experimental catchments were carried out in 2015 and 2016 rainy season. The average amount of loss of total N (8.36 kg $ha^{-1}y^{-1}$) and P (0.25 kg $ha^{-1}y^{-1}$) recorded at the outlet of the sub watershed (W-1) were higher than the average amount of loss of N (2.69 kg $ha^{-1}y^{-1}$), and P (0.054 kg $ha^{-1}y^{-1}$) observed at the nested gully catchment (W-2) in 2015 rainy period. The sediment associated soil nutrients loss in 2016 rainy period was 6.8 and 7.42 kg $ha^{-1}y^{-1}$ of N and 0.162 and 0.198 kg $ha^{-1}y^{-1}$ of P from W-1 and W-2, respectively. The change in quantity between the years was due to the change in amount and distribution of rainfall that affected the sediment and runoff generated from the catchments.

The monthly loss of N is directly proportional to the estimated soil loss in both rainy seasons. In 2015, unlikely to N, P is highest in August at W-1 than other period which is likely due to saturation of the bottom lands dominated by vertic nitosols and increasing in sediment concentration from the gully banks (Fig. 9). Nutrients eroded or

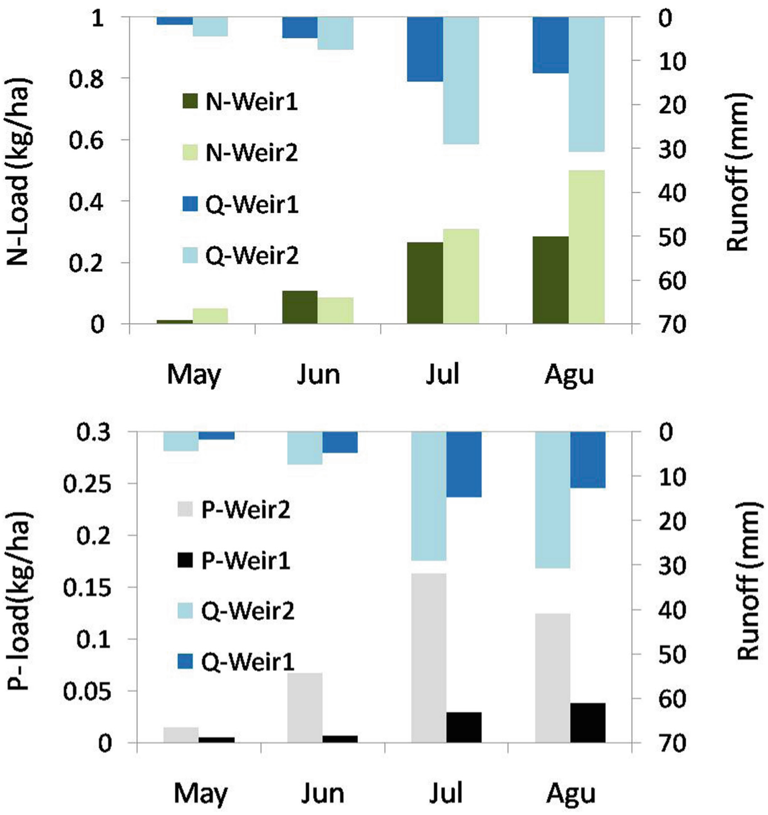

Fig. 8. Monthly dissolved nutrients lost and runoff depth in 2016 rainy season

leached from soil are also subjected to the rate of uptake by the crops as they stay in the soil. In the study watershed, most of the crops were sown from mid of June to end of July when fertilizer is frequently applied. The result indicated that the nutrients loss was significantly high starting from July (mostly at the time of full application of fertilizer) and gets reduced to the next months (Figs. 9 and 10). When tillage is reduced or eliminated, particulate nutrient loss in surface runoff usually declines. Timing and methods of application of fertilizer are more important to control nutrients transported in runoff because nutrients transport with soil tends to increase with increasing nutrient concentration at the soil surface and increasing soil losses [31]. Agricultural practices that reduce nutrient concentrations in the soil surface and reduce surface runoff, therefore, are most effective in controlling nutrient transport.

A statistical test (F-test) at 5% significance level was carried out to compare the particulate and dissolved nutrient loss. The nitrogen loss at W-1 was significantly different among dissolved and particulate nutrient loss. Phosphorus was not statistically different between the particulate and dissolved nutrient loss at both outlets. This indicates that phosphorus is considerably leached by surface runoff.

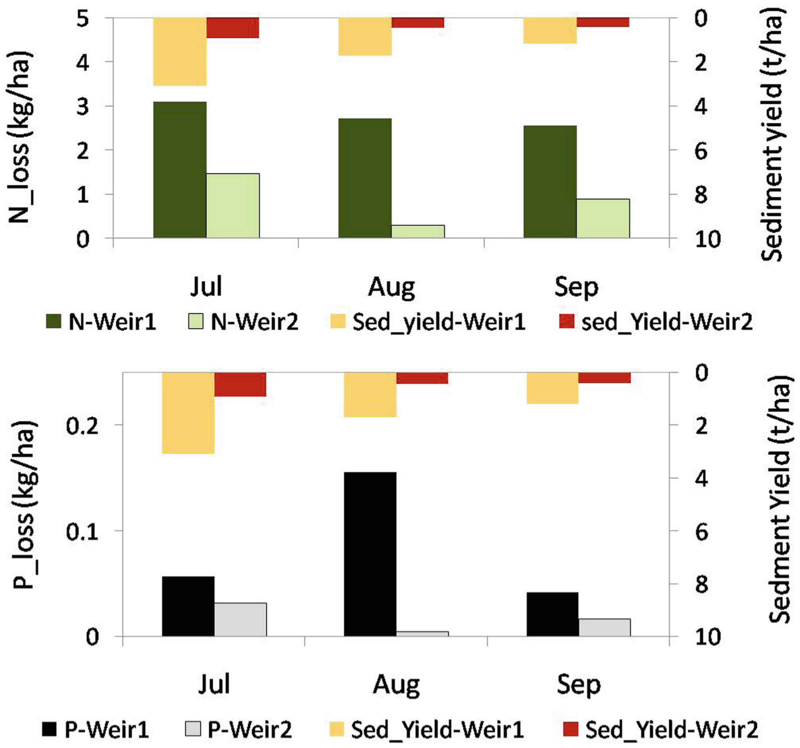

Fig. 9. Monthly distributed sediment yield and sediment associated soil nutrients loss in 2015

Few studies are available on nutrient losses in Ethiopia. The study [21] found that annual average national nutrient losses of N and P in Ethiopia were 79 kg ha^{-1}y^{-1} and 5 kg ha^{-1}y^{-1}, respectively. However, [32] reported smaller losses (35 and 0.2 kg ha^{-1} y^{-1}) of N and P, respectively from the cultivated lands of Tigray (northern Ethiopia). In other studies conducted in Dapo, Mizewa and Meja watersheds in Blue Nile basin, the average nutrients loss for N was 14, 2.1 and 9.7 kg ha^{-1} y^{-1}, respectively. Whereas, 6.8, 1.9 and 4.7 kg ha^{-1} y^{-1} of P was lost, respectively [33]. Further studies were conducted on nutrient loss in sub-Saharan Africa. The alarming annual average nutrient loss for sub-Saharan Africa was 22 kg N ha^{-1} y^{-1}and 2.5 kg P ha^{-1} y^{-1} in 1982–84, and 26 kg N ha^{-1} y^{-1} and 3 kg P ha^{-1} y^{-1} in 2000 [20]. According to the report by [34] the estimated TN and P export from the watersheds in the Mid-Atlantic region is 9.0 kg ha^{-1} y^{-1} and 0.68 kg ha^{-1} y^{-1} respectively. In this study, the N and P lost is still lower than the above mentioned watersheds except Mizewa and Meja watersheds [33] for N lost and [32] studies for P. The extent of soil erosion, rainfall characteristic, watershed size, management practice, fertility status and other variables could be mentioned as causes for variation of nutrient loss in the country.

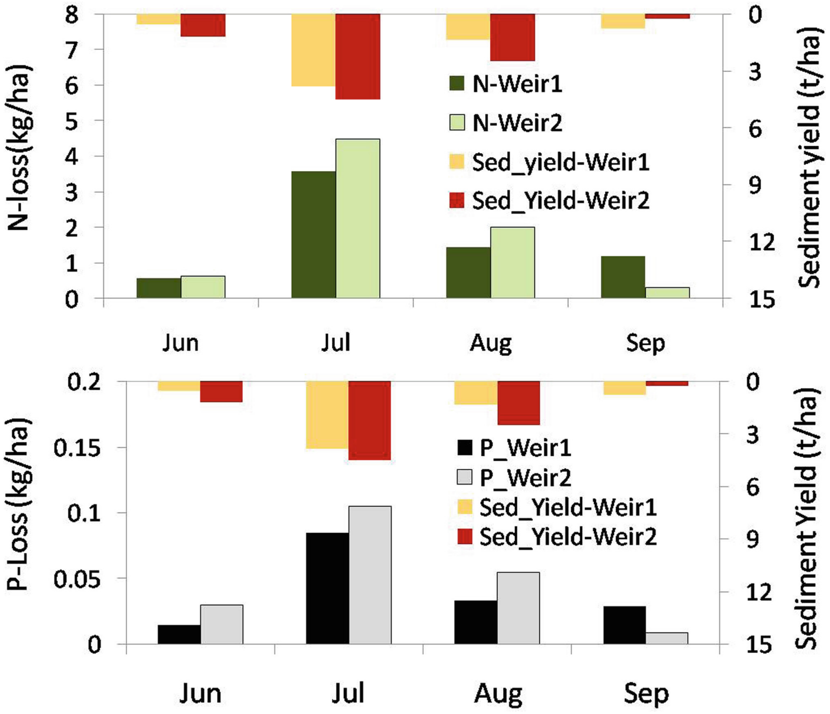

Fig. 10. Monthly distributed sediment load and sediment associated nutrients losses in 2016

Table 2. Statistical comparison of variables among particulate and dissolved nutrient loss using 5% significance level

Variable	Dissolved vs particulate soil nutrients loss	
	Outlet	Nested
N	0.0039	0.011
P	0.165	0.387

4 Conclusion

Dissolved nutrients (N and P) lost in surface runoff were low for each of the two study years than sediment associated nutrient lost. There is statistically significance difference among particulate and dissolved N lost in both outlets, because of agricultural area extent difference while there was no significant difference for P. Dissolved soil nutrients (N and P) lost in runoff was usually small at the beginning of the cropping season and increased progressively throughout the rainy season. Sediment associated soil nutrients (N and P) were usually highest at the beginning of cropping time and decreased progressively throughout the rainy season. Nutrient transport by runoff tends to increase with increasing amount of rainfall and runoff due to leaching. The study suggested that there is a seasonal difference related to progressive removal of soil nutrients by runoff and sediment. Therefore, this seasonal difference should be in to consideration while designing practices to control nutrient losses during critical runoff and erosion periods. Losses of nutrient (N and P) associated with runoff and soil erosion can be greatly reduced by effective soil erosion control practices since a large component of the total nutrients lost is associated with the sediment than dissolved nutrient lost.

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