

1     **Sediment Concentration Rating Curves for a Monsoonal Climate: upper**  
2                                    **Blue Nile**

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14  
15    **Abstract**

16    Information on sediment content in rivers is important for design of reservoirs and for  
17    environmental applications. Because of scarcity of continuous sediment data, methods  
18    have been developed to predict sediment loads based on few *discontinuous*  
19    measurements. Traditionally, loads are being predicted using rating curves that relate  
20    sediment load to discharge. The relationship assumes inherently a unique relationship  
21    between concentration and discharge and therefore although performing satisfactorily in  
22    predicting loads, it may be less suitable for predicting concentration. This is especially true  
23    in the Blue Nile basin of Ethiopia where concentrations decrease for a given discharge with  
24    the progression of the rainy monsoon phase. The objective of this paper is to improve the  
25    sediment concentration predictions throughout the monsoon period for the Ethiopian

1 highlands with a modified rating type equation. To capture the observed sediment  
2 concentration pattern, we assume that the sediment concentration was at the transport limit  
3 early in the rainy season and then decrease linearly with effective rainfall towards source  
4 limited concentration. The modified concentration rating curve was calibrated for the four  
5 main rivers in the Lake Tana basin where sediment concentrations affect fish production  
6 and tourism. Then the scalability of the rating type equation was checked in three hundred  
7 hectare watersheds for which historic data was available. The results show, that for  
8 predicting sediment concentrations, the (modified) concentration rating curve was more  
9 accurate than the (standard) load rating curve as expected. In addition loads were predicted  
10 more accurately for three of the four rivers. We expect that after more extensive testing over  
11 a wider geographical area, the proposed concentration rating curve will offer improved  
12 predictions of sediment concentrations in monsoonal climates.

13 **Key Words:** Africa, Horn of Africa, Ethiopia, Erosion, Tropics, Soil

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## 1 **1 Introduction**

2 Only for a few rivers in the world and over a limited period, sediment concentrations have  
3 been measured at a daily or shorter frequency. In order to determine sediment loads in the  
4 absence of these measurements, models and rating curves have been used. Knowing the  
5 total sediment loads from rivers is essential for evaluating the siltation of reservoirs (Ali et  
6 al., 2014), assessment of soil erosion and nutrient loss (Walling, 1977). As a result  
7 knowledge of sediment concentration is important in most environmental applications  
8 because among others it hampers fish reproduction and reduce the esthetic value of  
9 surface waters (Vijverberg et al. 2012).

10 In the Blue Nile Basin, where the construction of the Grand Ethiopian Renaissance Dam is  
11 and planning of other hydroelectric dams are under way, determining sediment loads is  
12 becoming more urgent. At the same time concern for the environment has been increasing  
13 and it has been noted that the fish production in Lake Tana is decreasing due to increasing  
14 sediment concentrations (Vijverberg et al. 2012). Thus, the ability to predict accurately the  
15 sediment concentrations and loads to the lakes and man-made *reservoirs* has become  
16 important in the Ethiopian highlands where *these* are not available.

17 Modeling sediment loss is fraught with difficulties that unlike runoff is not bounded by the  
18 amount of rainfall. So there is no upper bound for sediment load in the absence of data.  
19 The models most commonly used for predicting soil loss are the USLE (Wischmeier and  
20 Smith,1965) and its derivatives such as RUSLE (Renard et al., 1991) and MUSLE (Williams  
21 and Berndt, 1977) Hydrologic Engineering Center River Analysis System, (HEC-RAS, HEC  
22 1995), Water Erosion Prediction Technology (WEPP, Nearing et al., 1989), Agricultural  
23 Non-Point Source Pollution (AGNPS, Young et al.1989), Erosion Productivity Calculator  
24 (EPIC,Jones et al., 1991), Soil and Water Assessment Tool (SWAT, Arnold et al., 1998)

1 and Chemicals, Runoff and Erosion from Agricultural Environment Systems (CREAMS,  
2 Knisel, 1980). More sophisticated models used are the Neural Differential Evolution (NDE),  
3 Artificial Adaptive Neuro-fuzzy inference system (ANFIS), and Artificial Neural Network  
4 (ANN) Models (Masoumeh and Mehdi, 2012; Özgür, 2007). However, it is cumbersome to  
5 obtain the required data for these models especially in developing countries. The reason is  
6 that these models were originally developed for areas that have large amounts of data. For  
7 example, in the land use and land cover map, the leaf area index data that SWAT needs is  
8 not available. Similarly, the soil data in Ethiopia is very coarse and is missing basic  
9 information such as soil texture, hydraulic conductivity and other parameters that are  
10 difficult to measure in Ethiopia. Additional challenges using these models are: i) the models  
11 have been developed in regions with a semi-arid temperate climate where the runoff  
12 mechanisms are governed by Infiltration excess unlike the highland areas where saturation  
13 excess runoff is dominating (Steenhuis et al., 2009; Bayabil et al., 2010; Tilahun et al.,  
14 2013) and ii) almost all of the models need intensive data with many parameters that might  
15 be available centrally in developed countries but not in developing countries such as  
16 Ethiopia. Therefore, historically when concurrent concentration and discharge  
17 measurement were taken at irregular intervals; rating curves were often the preferred  
18 choice for predicting sediment loads (e.g., Walling, 1990) but also recently (e.g., Horowitz,  
19 2010); Kokpinar et al., (2015); Choi and Lee, 2015; Kheirfam and Vafakhah, 2015). The  
20 abundance of papers on load rating curves in the refereed literature should be not  
21 surprising since purpose of the measurements was to determine the amount of sediment  
22 that potentially could be deposited in rivers and reservoirs. In the literature, a limited  
23 number of articles developed sediment rating curves. These few studies were carried out in  
24 Sweden (Fenn et al., 1985); Ontario Canada (Irvine and Drake, 1987), British Columbia in  
25 Canada (Sichingabula, 1998), South Australia (Sun et al, 2001) and for the Himalayan

1 glacier in India (Arora et al., 2014). Thus, compared to the sediment load rating curves that  
2 are available throughout the world for many rivers, there are very few sediment  
3 concentration rating curves and none for a monsoon climate.”

4  
5 There is a connection between models and rating curves in sediment studies. Rating curves  
6 have been used to validate models. Previous simulations to predict sediment load in the  
7 Lake Tana basin such as Easton et al. (2010) and Setegn et al. (2009b), sediment load  
8 rating curves were used to generate the observed sediment load data and validate the  
9 models. Developing better rating curves will result in better predictions generated from  
10 observed flows.

11 There are at least 20 different ways to convert the measured concentration and discharge  
12 data to a rating curve (Phillips, et al., 1999; Horowitz, 2010). The most often used is a  
13 power function that relates sediment load (product of discharge and concentration) to  
14 discharge, (Miller, 1951; Muller and Foerstner, 1968; Phillips, et al., 1999; Masoumeh and  
15 Mehdi, 2012).

$$16 \quad M = a_l Q^b \quad (1)$$

17 where  $M$  is the sediment load,  $Q$  is the discharge and  $a_l$  and  $b$  are rating curve parameters  
18 determined by regression analysis using observed data (Gao, 2008).

19 The concentration,  $C$ , can be found by dividing the load (Eq. (1)) with the discharge  $Q$ ,

$$20 \quad C = a_c Q^{b-1} \quad a_c = a_l \quad (2)$$

21 The load rating curve Eq. (1) inherently assumes a unique relationship between discharge  
22 and concentration (i.e.,  $a_c$  is constant, Gao, 2008). However when observed sediment  
23 concentrations are plotted against discharge, there is usually significant scatter around the

1 curve (Asselman, 2000, Gao 2008 and Walling 1977) indicating that other factors in  
2 addition to discharge influence sediment concentrations. To compensate for variations,  
3 various modifications have been applied; these include dividing the sediment discharge  
4 data into seasonal or hydrologic groupings, applying various correction factors, or using  
5 non-linear regression equations (Horowitz, 2010; Phillips, et al., 1999); In the Ethiopian  
6 highlands the scatter in the plot of discharge and sediment concentration is caused by the  
7 fact that the observed sediment concentrations in streams and rivers are decreasing for the  
8 same discharge with the progression of the rainy phase as shown for the Ethiopian  
9 highlands by Guzman et al. (2013) and Tilahun et al. (2013c). The same pattern has also  
10 been observed in Tibet in the upper reaches of watersheds by Henck et al. (2010).

11 Various reasons are given for the decrease in concentration with the progression of the  
12 rainy phase: Tilahun et al. (2013b) poses that with the progression of the rainy phase of the  
13 monsoon the value of  $a_c$  is a function of the portion of newly plowed land takes the highest  
14 value in the beginning of the rainy season when in the unconsolidated soil rills form and the  
15 soil removed is transported by runoff. Nyssen et al. (2004), Vanmaercke et al. (2010), and  
16 Asselman (1999) showed that the sediment concentration depends on the sediment  
17 available for transport by runoff. Haile et al. (2006) and Awulachew et al. (2009) relate  
18 sediment concentration to the amount of plant cover protection which is increasing towards  
19 the end of the rainy period. However, Tebebu et al. (2010) noted that plant cover and  
20 sediment concentration were not statistically related. Zumar et al (2015) noted that sediment  
21 transport originated from *saturation* excess interflow from sloping agricultural fields and was  
22 not related to plant cover. Zegeye et al. (2010) and Tilahun et al. (2013c) attributed the  
23 decreased loading with the cessation of the rill formations. In addition, the base flow  
24 increases at the end of rainy phase and dilutes the sediment concentrations.

1 Since the traditional method of determining rating curves for sediment loads assumes that  
2 the sediment concentrations are a unique function of the discharge, this method cannot be  
3 used in environmental applications for predicting sediment concentrations when the  
4 sediment concentration decreases throughout the season for a given amount of discharge.  
5 The objective of this paper is, therefore, to develop a realistic method in determining the  
6 decreasing sediment concentration with the progression of the monsoon using the limited  
7 data common in most of the tropics. The study is carried out in the Ethiopian highlands.  
8 Two groups of watershed sizes were selected to test how well the concentration rating  
9 curve performed. These consisted of four major rivers and their watersheds in the Lake  
10 Tana basin and three small well-monitored 100 ha watersheds *in another part of the Blue*  
11 *Nile basin.*

12 **2 THEORY: CONCENTRATION RATING CURVES**

13 To include the observed decreasing sediment concentration with the progression of the  
14 rainy season in predicting sediment concentrations, Steenhuis et al. (2009) and Tilahun et  
15 al. (2013b,c) adapted the theory originally developed by Hairsine and Rose (1992). This  
16 relationship as depicted in Fig.1 is based on the assumption that the sediment load in the  
17 beginning of the rainy monsoon phase is at the transport limit when sediment is available  
18 from the plowed land and then linearly decreases with cumulative effective rainfall to a  
19 source limited concentration. Source limiting describes the condition when the rate of  
20 detachment from the soil determines the sediment concentration. Transport limiting, occurs  
21 when *deposited and detached sediment* are in equilibrium and the stream carries *its*  
22 maximum amount of sediment (Foster and Meyer, 1975). This is the case in the Ethiopian  
23 highlands when fields are plowed in the beginning of the rainy monsoon phase. Once the rill  
24 network is fully developed and stable, the sediment concentration will become source

1 limited (Tilahun et al. 2013b). Finally as the surface runoff ceases and only base and  
 2 interflow feeds the river, there will be small amount of sediments that the water picks up  
 3 from the river bed or stirred up by animals or humans. Therefore, the sediment  
 4 concentrations were calculated separately during the rainy monsoon phase and during the  
 5 dry phase. Since the start of the rainy phase varies from year to year and from one location  
 6 to another, we will use the cumulative effective rainfall,  $P_e$ , to replace the “time” parameter.  
 7  $P_e$  is determined by summing the daily effective rainfall which is equal to precipitation minus  
 8 the potential evaporation for that day. The rainy phase starts when the cumulative effective  
 9 rainfall,  $P_e$  is greater than 40 mm (from observation) and setting each time when  $P_e$  is  
 10 negative to zero. As we will see later in most of the Lake Tana basin this occurs in the  
 11 beginning of July , but it begins in mid-May in Gilgel Abay because the rainy phase starts  
 12 earlier in a southern direction. For all of the watersheds the rainy phase ends the beginning  
 13 of October

14 Based on these observations we redefine the “ $a_c$ ” in Eq. (2) for the rainy phase as:

$$\begin{aligned}
 a_c &= \left[ a_t + (a_s - a_t) \frac{P_e}{P_T} \right] & \text{for } P_e < P_T \\
 a_c &= a_s & \text{for } P_e \geq P_T
 \end{aligned} \tag{3}$$

16 where  $a_s$  is sediment source limiting factor,  $a_t$  is the sediment transport limiting factor,  $P_e$  is  
 17 the cumulative effective rainfall (mm) at a particular day,  $P_T$  is the threshold cumulative  
 18 rainfall up to *Which* amount the  $a_c$  parameter linearly decreases with cumulative rainfall,  $P_e$ ,  
 19 and after which the sediment concentration remains at the source limit. Thus, when  $P_e$  is  
 20 equal to *or* greater than  $P_T$ , the ratio becomes one, which indicates that the sediment  
 21 concentration is equal the source limit. The “ $a_c$ ” and “ $a_s$ ” parameters *depend* on a number of  
 22 factors such as slope length, particle size and disposability. In addition, “ $a_s$ ” parameter



1 varies with the cohesion of the soil (Yu et al., 1997). The threshold value was found in other  
 2 simulations to be around 600 mm (Tilahun et al., 2013 a, b). The values of all three  
 3 parameters are therefore difficult to predict a priori and need to be calibrated. As we will see  
 4 hereafter they are in relatively narrow range indicating that they have some physical  
 5 meaning.

6 The value of the exponent b in Eq. (1) can be set to 1.4 when there is a linear relationship  
 7 between velocity and sediment concentration and the depth of water is small compared to  
 8 its width (Ciesiolka et al., 1995; Yu et al., 1997; Tilahun et al., 2013a b c). Using this value  
 9 for b and combining Eq. (2) and (3), the modified concentration rating curve can be written  
 10 for the rainy phase as:

$$\begin{aligned}
 C &= \left[ a_t + (a_s - a_t) \frac{P_e}{P_T} \right] Q^{0.4} & \text{for } P_e < P_T \\
 C &= a_s Q^{0.4} & \text{for } P_e \geq P_T
 \end{aligned}
 \tag{4a}$$

12 For the dry monsoon phase the concentration is

$$C = a_b Q^{0.4}
 \tag{4b}$$

14 The modified load rating curve can be obtained by multiplying Eq. (4) by Q. Then, for the  
 15 rainy phase the load, M can be expressed as:

$$\begin{aligned}
 M &= \left[ a_t + (a_s - a_t) \frac{P_e}{P_T} \right] Q^{1.4} & \text{for } P_e < P_T \\
 M &= a_s Q^{1.4} & \text{for } P_e \geq P_T
 \end{aligned}
 \tag{5a}$$

17

And for the dry monsoon M can be expressed as:

1  $M = a_b Q^{1.4}$  (5b)

2

### 3 **3 Materials and methods**

4 The load rating curve (Eqs. (1) and (2)) and concentration rating curves (Eqs. (4) and (5))  
5 are evaluated for the rivers in the four major watersheds in the Lake Tana basin: Gilgel  
6 Abay, Gumara, Megech and Ribb. These are named, hereafter, as the “Lake Tana  
7 Watersheds”. In addition, three small (approximately 100 ha) watersheds are selected for  
8 the assessment of scale effects in the concentration rating curve: Anjeni, Debre Mawi and  
9 Maybar. We will call these hereafter “100-ha watersheds”.

#### 10 **3.1 Description of study areas**

11 The 15,000 km<sup>2</sup> Lake Tana basin is in the headwaters of the approximately 180,000 km<sup>2</sup>  
12 Blue Nile basin. The average annual discharge from Lake Tana is 3.8\*10<sup>9</sup> m<sup>3</sup> (3.8 BCM)  
13 which is approximately 7% of that of the Blue Nile at the Ethiopian Sudanese border  
14 (Awulachew et al., 2009). The elevation in the basin ranges from 1787 m to 4260 m. The  
15 major rivers that contribute 93% of the inflow to the lake are Gilgel Abay, Rib, Gumara and  
16 Megech. The gaging stations are located 95, 20, 26 and 40 km, respectively, to the lake  
17 inlet as shown in Fig. 2. The three micro watersheds are Debre Mawi, Anjeni and Maybar.  
18 The 91ha Debre Mawi and the 113ha Anjeni are located in the Blue Nile basin south of  
19 Bahir Dar at 35 km and 220 km respectively. The 112ha Maybar is just located on the  
20 boundary of the Blue Nile Basin near Dessie 300 km east of Bahir Dar. Average annual  
21 rainfall for all watersheds in this study varies between 1100 to over 1900 mm yr<sup>-1</sup> (Table 1).

#### 22 **3.2 Available Data**

##### 23 **3.2.1 Discharge and sediment concentrations**

1 Irregular measured discharge and sediment concentration data by Ministry of Water  
2 Irrigation and Energy (MoWIE) for the major four rivers in Lake Tana basin were available  
3 from 1964 to 2008. The numbers of observations available for the Lake Tana watersheds  
4 used for this analysis period were 23, 53, 52 and 16 for the Gilgel Abay, Gumara, Ribb and  
5 Megech watersheds, respectively. The data of the 100-ha watersheds were collected for  
6 Anjeni and Maybar by ARARI (Amhara Region Agricultural Research Institute). The Debre  
7 Mawi data were collected partly by ARARI and us and is described in Tilahun et al. (2013 a,  
8 b).

9 The sediment concentrations in the Lake Tana watershed has been increasing since the  
10 initial measurement were made in 1964 (Ayana et al. 2014). We selected the following  
11 periods for analysis 1968-2008 for Gilgel Abay, Gumara and Rib. The Megech data was  
12 only available and the analysis was made for 1990–2007. The analysis for the Anjeni was  
13 made for 1996 and for Anjeni in 1994 when the watershed were stabilized from the soil and  
14 water conservation practices that were installed in the mid of 1980's. For the Debre Mawi  
15 watershed the data in the years 2010 and 2011 were used before large scale conservation  
16 practices were installed in 2012.

17 **Climate data:** Rainfall and temperature data for the Lake Tana watersheds (Table 1) were  
18 available from 1994 to 2008 by the National Metrological Agency of Ethiopia (NMAE), Bahir  
19 Dar branch. The areal rainfall was calculated by using Thiessen-polygon method for the  
20 available rainfall stations for the Lake Tana watersheds as these watersheds have two or  
21 more rainfall stations. The method was chosen because it *is* simple and does not require  
22 additional information. Details are given in the supplementary materials (Supplementary  
23 Material, Table A1). The Anjeni and Maybar precipitation and temperature measured in the  
24 watershed were made available by ARARI. The precipitation data for Debre Mawi was

1 collected by us on site. To fill the missing data the gage at Adet (8 km away) was used.  
2 Temperature was obtained for the Adet station from the Adet Agricultural Research Center.

3 **Potential evapotranspiration** was estimated based on observed temperature data with the  
4 method developed by Enku and Melesse (2013).

5 **Effective precipitation** was calculated by subtracting the evaporation from rainfall each  
6 day. Cumulative effective precipitation was calculated during the rainy phase of the  
7 monsoon.

### 8 **3.3 Methods**

9 Rating curves were determined by either fitting the loads (i.e., the load rating curve) or the  
10 concentrations (concentration rating curve). Note that both the load and concentration  
11 rating curves can predict both the load and the concentration and thus the naming is based  
12 on the method of determining the rating curve.

13 **The sediment load rating curve:** The original MoWIE load rating curve was obtained for  
14 the Lake Tana watersheds by linearly regressing the logarithm of the sediment load versus  
15 the logarithm of the discharge for the period from 1964-2008. The slope of the line is  $b$  in  
16 Eq. (1) and the intercept gives the value of  $a_1$ . These are listed in Table 1. In addition, we  
17 followed the same procedure to determine the rating curve for the 100-ha watersheds  
18 Sediment concentrations were determined by dividing the load with the corresponding  
19 discharge.

20 **The concentration rating curve:** Rating curve was found by regressing the observed  
21 sediment concentrations and the discharge with Eq. (4). Four fitting parameters were  
22 required: Three for the rainy phase, i.e., the amount of rainfall  $P_T$  after which the sediment

1 is at the source limit and the source limiting factor  $a_s$  and a transport limiting factor  $a_t$ . For  
2 the dry phase the parameter,  $a_b$ , was required for the concentration in the base flow.

3 *For the Lake Tana watersheds, precipitation and evaporation were only available for 1992-*  
4 *2000. In order to establish a  $P_T$  value for the entire period for which discharge and sediment*  
5 *data were observed, average cumulative effective precipitation for the years from 1992-*  
6 *2000 as a function of the day was calculated for each watershed. For the 100-ha*  
7 *watersheds the average daily sediment concentrations and discharge and total rainfall data*  
8 *were available for the same years and the actual values of cumulative effective precipitation*  
9 *were used. Initial values for calibrating parameters ( $a_t$  and  $a_s$ ) were based on Tilahun*  
10 *(2013a, b) for Debre Mawi watershed. These initial values of ( $a_t$ ,  $a_s$  and  $P_T$ ) together with  $a_b$*   
11 *were changed systematically till the best “closeness” or “goodness-of-fit” was achieved*  
12 *between measured and predicted sediment concentrations. The loads were obtained simply*  
13 *by multiplying the predicted concentrations by the observed discharge.*

#### 14 **3.4. Statistical analysis**

15 We first tested for outliers and those either less than half or more than twice the expected  
16 discharge or concentrations were removed from further analysis. In none of the cases not  
17 more than 5 % the data points were discarded. The goodness of fit of the rating curves  
18 were determined with the correlation coefficient ( $R^2$ ) and the Nash Sutcliff coefficient (NS).  
19 The goodness of fit for model performance was based on Moriasi et al. (2007), and rated as  
20 very good for  $NS > 0.75$ ; good, when NS values was between 0.75 and 0.65; rated as  
21 satisfactory for values less than 0.65 but more than 0.5 and finally values less than 0.5 was  
22 considered poor

23

## 1    **4. RESULTS**

### 2    **4.1 Lake Tana watershed**

#### 3    **4.1.1. Observed sediment concentration and load**

4    The available sediment concentration data for the Lake Tana watersheds calculated from  
5    the sediment load of the Ministry of Water Irrigation and Electricity (MoWIE) are shown in  
6    Fig. 3. There were three periods when samples were taken for determining the rating curve.  
7    These were from 1964-1968, 1980-1996 and 2004-2008 (Fig. 3a and Supplementary  
8    Material, Tables B1 - B4). Gumara and the Ribb have the richest data set and the Gilgel  
9    Abay with only 23 data pairs is the poorest. Gumara and Ribb have also the greatest  
10   concentrations (Fig. 3). The concentration from the Megech is the smallest likely due to the  
11   Angereb man-made reservoir (which provides water supply for Gonder town) which was  
12   constructed in early 1980s.

13   When these concentration are plotted as a function of the day of the year independent of  
14   the year (Fig. 3b), the familiar pattern appears with the concentrations usually small in the  
15   base flow period form early October to the start of the rainy phase when concentrations  
16   increase. The elevated concentrations start around May 15 in the Gilgel Abay watershed  
17   which is earlier than the other watersheds because the rain starts earlier in this part of the  
18   watershed. The concentrations in the other watersheds start to increase in the late June  
19   (Table 2) and beginning of July The maximum concentration occurs in late June and early  
20   July (Fig. 3b) while the discharge is still relatively small (Fig. 3c) and decrease with  
21   progression of the rainy phase *while discharge is elevated*.

22

### 1 **4.1.2 Evaluation of sediment concentration predictions**

2 The relationship between the observed vs predicted sediment concentration for the Lake  
3 Tana watersheds are presented in Fig. 4 and the fitting statistics in Table 3. Both the  
4 concentration and sediment rating curves are used for obtaining the predicted sediment  
5 concentrations. Note that the concentration sediment rating curve refers to Eq. (4) and (5)  
6 and involves four fitting parameters. Best fit values are shown in Table 2. The  
7 concentrations with the load rating curve are obtained by fitting the loads first and then  
8 obtaining the concentrations by dividing the load by the discharge. Here we use the values  
9 obtained by MoWIE load rating curve in Table 1.

10 For the Lake Tana watersheds, the sediment concentrations are under predicted by the  
11 MoWIE load rating curve and indicated poor prediction performance (Table 3, Fig 4). The  
12 concentration rating curve fits the concentrations satisfactory with Nash Sutcliff values of  
13 0.52 to 0.61 and  $R^2$  values of 0.46 to 0.73 with slopes close to one (Table 3, Fig 4) The  
14 MoWIE load rating curves are poor in predicting concentrations.

### 15 **4.1.3 Evaluation of sediment load predictions**

16 Using the same rating curve parameters as in the concentration predictions above, the  
17 observed vs predicted sediment loads for the Lake Tana watersheds are shown in Fig. 5  
18 and the goodness of fit in Table 4. The sediment loads (Fig. 6) are predicted satisfactorily  
19 to good with both the MoWIE load and concentration rating curves for Gilgel Abay, Ribb  
20 and Megech with  $R^2$  values ranging from 0.61-0.84 (Fig. 5). The MoWIE load rating curve  
21 predicted the sediment load poorly for Gumara watershed. Generally, for the Lake Tana  
22 watersheds the concentration rating curves predict the loads more accurately than the  
23 MoWIE load rating curves with  $R^2$  of 0.64-0.89 (Table 4) and slopes between 0.72 and  
24 0.94 (Fig. 5).

## 1 **4.2 Results of the three 100-ha watersheds**

2 After testing the sediment concentration rating curves for the Lake Tana watersheds, we  
3 investigated the applicability of the concentration rating curve for small watersheds. The  
4 three watersheds selected had good quality data. The concentration rating curve using Eq.  
5 (3) and (4) gave a reasonably good fit with the observed values (Fig. 6) with  $R^2$  values  
6 ranging from 0.60 to 0.63 (Table 3) with values for the transport coefficients similar to the  
7 Lake Tana watersheds. The source limiting factor for Anjeni was the greatest and likely was  
8 caused by large active gully with unconsolidated soil that easily could be picked up by the  
9 flowing water.

## 10 **5. Discussion**

11 We will first discuss the loads and concentration predictions in the Lake Tana basin with the  
12 two types of rating curves followed by a comparison of the sediment load and concentration  
13 prediction with the concentration rating curve for the 100 ha and Lake Tana watersheds.

### 14 **5.1 Predicting sediment concentrations (Lake Tana watersheds)**

15 Similar to the predictions of the loads, the concentration rating curve fitted the observed  
16 concentrations better than those predicted by the MoWIE load rating curve. In addition to  
17 the reasons given for the poor fit (i.e. number of fitting parameters and log-log fit), the  
18 inherent assumption of a constant sediment concentration for the MoWIE rating curve was  
19 clearly problematic for fitting observed concentrations. In the Ethiopian highlands  
20 concentration are far from constant and follow usually a typical pattern where the  
21 concentrations are elevated during the beginning of the rainy season and decrease with the  
22 progression of the rainy season (Fig 3b) while the discharge increases (Fig 3c). Again



1 similar to the loads, the Gilgel Abay fitted reasonably well because the concentrations were  
2 reasonably the same during the rainy phase (Fig 3b, black dots).

### 3 **5.2 Predicting sediment loads (Lake Tana watersheds)**

4 For the Lake Tana watersheds, the concentration rating curve (Eq. (4)) fitted the observed  
5 sediment load more accurately than the MoWIE load rating curve (Eq. (1)) as shown in Fig  
6 5. The only exception was the sediment load predictions for the Gilgel Abay (Fig. 5a) that  
7 was slightly better predicted by the MoWIE load curve than the concentration rating curves.  
8 One could expect that the concentration rating curve would perform better because it has 4  
9 fitting parameters compared to the MoWIE sediment rating curve with only two parameters.  
10 In addition, there were few measurements taken early in the rain phase when sediment  
11 concentrations could have been elevated (Fig 3).

12 However this does not explain the unexpected poor fit with slopes of much less than 1 for  
13 the remaining three watersheds in the Lake Tana basin (indicating that the sediment loads  
14 for the large storms are severely under predicted). This poor fit for the three watersheds  
15 originates from using the log transformed values for fitting the sediment load and discharge.  
16 To demonstrate that the MoWIE log rating curve fits the log transformed values well we re-  
17 plotted Fig 5a in the auxiliary material (Supplementary Material, Fig C1) with a log scale.  
18 The log transformed values give more weight to the small values of parameters than the  
19 larger values. Thus, indeed using the log scale a good fit was obtained, while the same  
20 points in the non-transformed values fit poorly (Fig 5a).

### 21 **5.3 Concentration rating curve (100 ha and Lake Tana watersheds)**

22 All fitting parameters for the concentration rating curve were remarkable independent of the  
23 size of the watershed (Table 2). There was not a systemic difference in parameter values

1 for the seven watersheds. The amount of effective rainfall ( $P_e$ ) after which the concentration  
2 became independent of the rainfall (i.e., Eq. (4b)) varied between 561mm/year for the Gilgel  
3 Abay and 599 mm/year for the Debre Mawi watershed. The difference among these values  
4 in all watersheds was not significant.

5 In further discussion of the sediment transport parameters we will exclude the Megech,  
6 since the gage station is located below the reservoir. Sediment is deposited in the reservoir  
7 and the parameters are not representative of the watershed that is subject to heavy  
8 gullyng. For the remaining six watersheds, the source factor  $a_s$  varied from 0.7 g/l  
9  $(\text{mm/day})^{-0.4}$  for Maybar to 1.8 g/l  $(\text{mm/day})^{-0.4}$  for Anjeni. The smaller values are related to  
10 watersheds with a minimum of gullyng such as Maybar. The greater values are associated  
11 with watershed with active gullyng such as Anjeni, Gumara and Debre Mawi (Table 2,  
12 Tilahun et al., 2015; Dagnew et al., 2015).

13 There was a threefold difference in transport coefficients (*but independent of watershed*  
14 *area as indicated in Table 2*). It varies in the Lake Tana basin between 1.6  $\text{g/L}^{-1} (\text{mm/day})^{-0.4}$   
15  $^{0.4}$  for the Gilgel Abay and 5.9  $\text{g/L}^{-1} (\text{mm/day})^{-0.4}$  for the Gumara. The basic assumption in  
16 the concentration rating curve is that the sediment concentrations are determined by the  
17 transport capacity after land is plowed and rills are formed. Differences in the value for the  
18 transport coefficient can be related to the slope of the watershed since the transport  
19 coefficients are dependent on the stream power and the stream power is a function of slope  
20 (Gao 2008). The Gilgel Abay has 22% of land in the lowest slope category (0-2%) which is  
21 three times that in Ribb and Gumara. Moreover, the Gilgel Abay has only 1% in slope of  
22 greater than 30% while the other watershed have 9% or more in this category. Similarly  
23 Anjeni, in which most land is terraced, has gentle slopes and a small transport coefficient  
24 compared to the Maybar and Debre Mawi watersheds that do not have terraces and have

1 agricultural land with greater slopes. In both Gilgel Abay (Fig. 3b) and the Anjeni (not  
2 shown) watersheds, the concentrations in the beginning of the rainy phase are less  
3 pronounced than the other four watersheds. Thus, the low value of the transport coefficient  
4 is most likely related to the slope of the cultivated land in the watershed.

5 Finally the “ $a_b$ ” values that determine the concentration during base flows are related to the  
6 stream channel erosion that in the case of the Gumara has the greatest value. This can be  
7 related to several factors mainly increasing population and activities for natural resource  
8 competition. This includes pumping water for irrigating cash crops during the dry monsoon  
9 phase from the river. In addition, sand is being mined from the river bed

## 10 **6. Conclusions**

11 In the Ethiopian highlands sediment concentrations in the rivers decrease with progression  
12 of the rainy phase of the monsoon. Using this observation while developing the sediment  
13 rating curve significantly improves for predicting the sediment concentration and load. The  
14 method developed by the Ministry of Water Irrigation and Energy and used for predicting  
15 daily loads throughout Ethiopia will likely remain the method of choice for most rivers  
16 especially for larger basins where concentrations remain relatively constant. Although more  
17 research has to be done, there is an indication that the coefficients in the newly developed  
18 concentration rating curve can be related to landscape characteristics. Therefore, these  
19 parameters might have physical meaning which would help to generate the parameters  
20 from the physical *watershed* characteristics for the *ungaged* catchments for predicting  
21 concentrations and load in the upper Blue Nile Basin.

22

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3 (USAID) through PEER Science program and Higher Education for Development (HED),  
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5 by Ministry of Water and Energy. We would like to thank MoWIE for making the rating curve  
6 data available to us.

7

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7

## **SUPPLEMENTARY MATERIAL**

Table A1: Thiessen weight derived from the Thiessen polygon method for estimating areal rainfall.

Table B1: Observed discharge and sediment data measured at the gauging station of Gilgel Abay watershed.

Table B2: Observed discharge and sediment data measured at the gauging station of Gumara watershed.

Table B3: Observed discharge and sediment data measured at the gauging station of Ribb watershed.

Table B4: Megech observed discharge and sediment data.

Figure C1: Log log transformed values of sediment load predicted by concentration MoW load rating curves for Gumara watershed.

## Tables

**Table 1.** Characteristics of the study watersheds in the Lake Tana Basin and the three 100 ha watershed in the Ethiopian highlands.

	Drainage Area (km <sup>2</sup> )	Mean Annual Rainfall(mm)	Rating curve (Eq.1) by MoWIE* load Rating Curve(RC) constants	
			a	b
Lake Tana watersheds				
Gilgel Abay	1665	1912	4	1.65
Ribb	1288	1213	30	1.59
Gumara	1274	1540	17.5	1.48
Megech	500	1455	15.1	1.35
100 ha watersheds				
Debre Mawi	0.91	1240	-	-
Anjeni	1.31	1658	-	-
Maybar	1.28	1320	-	-

MoWIE\*: Ministry of Water Irrigation Electricity.

**Table 2.** The calibrated sediment rating curve parameters and the specific dates where the sediment transport ends and the sediment limiting phase starts.

River Catchment	a factor calibrated values (g/l (mm/day) <sup>-0.4</sup> )		a factor for base flow ( <i>a<sub>b</sub></i> ) (g/l (mm/day) <sup>-0.4</sup> )	Threshold effective precipitation (mm)	The date where the <i>a<sub>s</sub></i> starts
	<i>a<sub>t</sub></i>	<i>a<sub>s</sub></i>	<i>a<sub>b</sub></i>	<i>P<sub>T</sub></i>	
Gilgel Abay	1.6	0.8	0.6	561	15-May
Gumara	5.9	1.5	0.7	574	15-Jun
Ribb	5.0	0.7	0.2	581	29-May
Megech	2.3	0.3	0.2	588	14-May
Maybar	5.1	0.7	-	598	15-May
Debre Mawi	6.9	1.1	-	599	5-Jun
Anjeni	3.1	1.8	-	596	27-May

**Table 3.** Performance of sediment concentration predicted by MoWIE load rating curve and the concentration rating curve.

River/ watershed/	MoWIE load rating curve		Concentration rating curve	
	NS	R <sup>2</sup>	NS	R <sup>2</sup>
Gilgel Abay	0.43	0.46	0.60	0.54
Gumara	-0.022	0.17	0.61	0.60
Ribb	-0.34	-0.22	0.52	0.73
Megech	0.035	0.07	0.52	0.56
Debra Mawi	-	-	0.69	0.60
Anjeni	-	-	0.63	0.63
Maybar	-	-	0.68	0.63

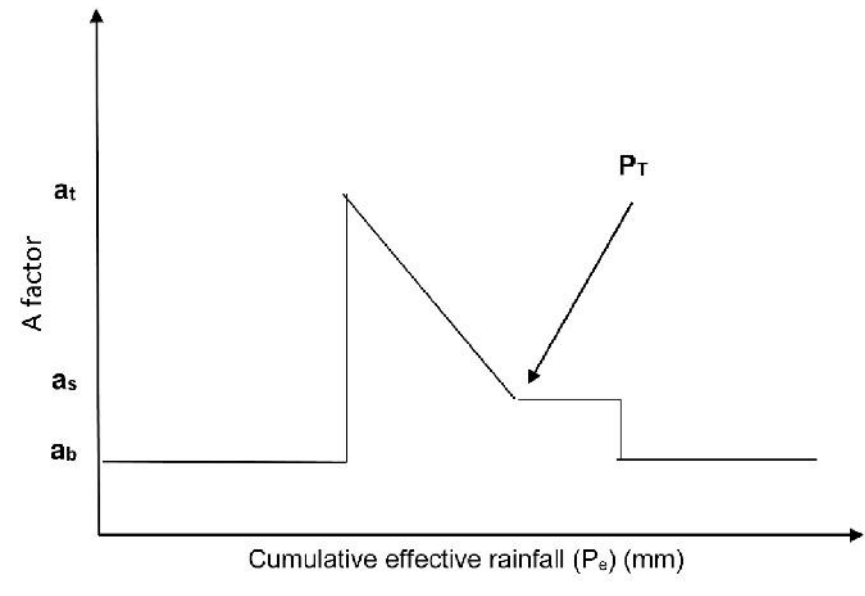
**Table 4.** Performance measures of sediment load predicted by MoWIE load rating curve and the concentration rating curve.

River/ watershed/	MoWIE load rating curve		Concentration rating curve	
	NS*	R <sup>2</sup>	NS	R <sup>2</sup>
Gilgel Abay	0.60	0.66	0.61	0.64
Gumara	0.21	0.20	0.65	0.69
Ribb	0.54	0.61	0.61	0.67
Megech	0.78	0.84	0.83	0.89

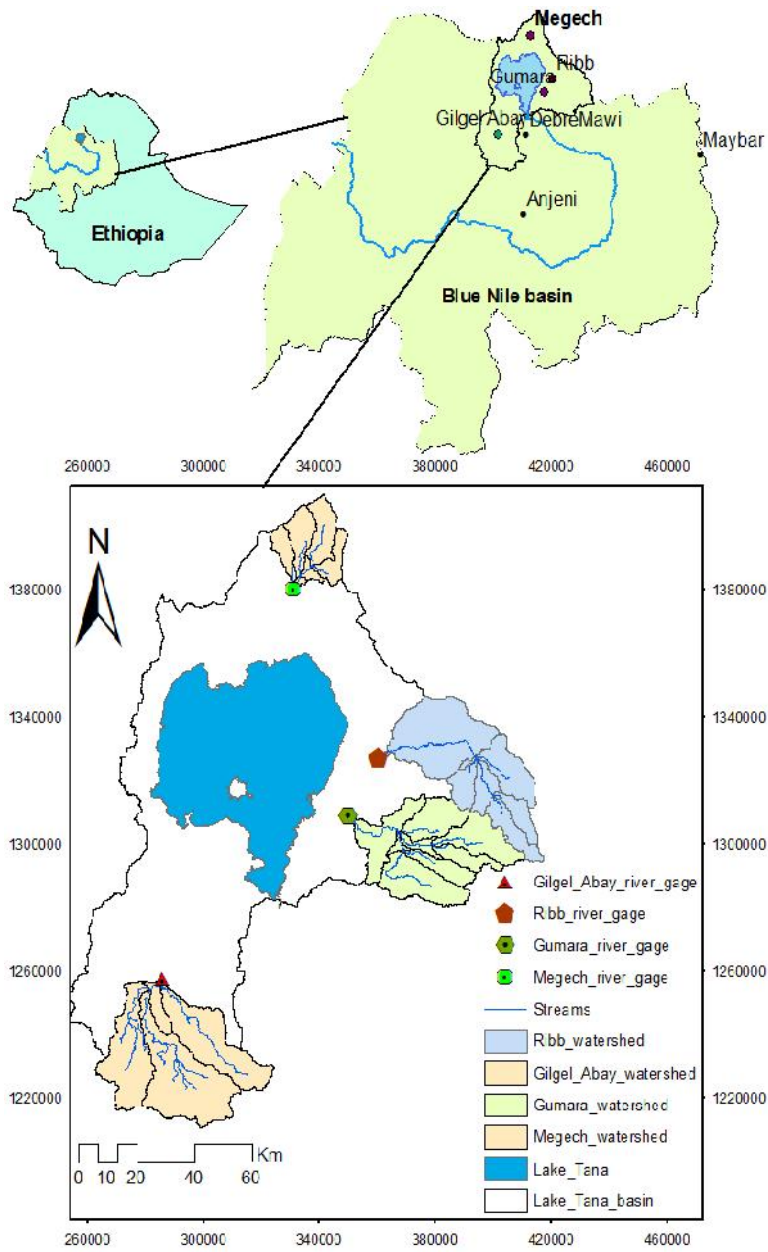
NS\* = Nash Sutcliff efficiency



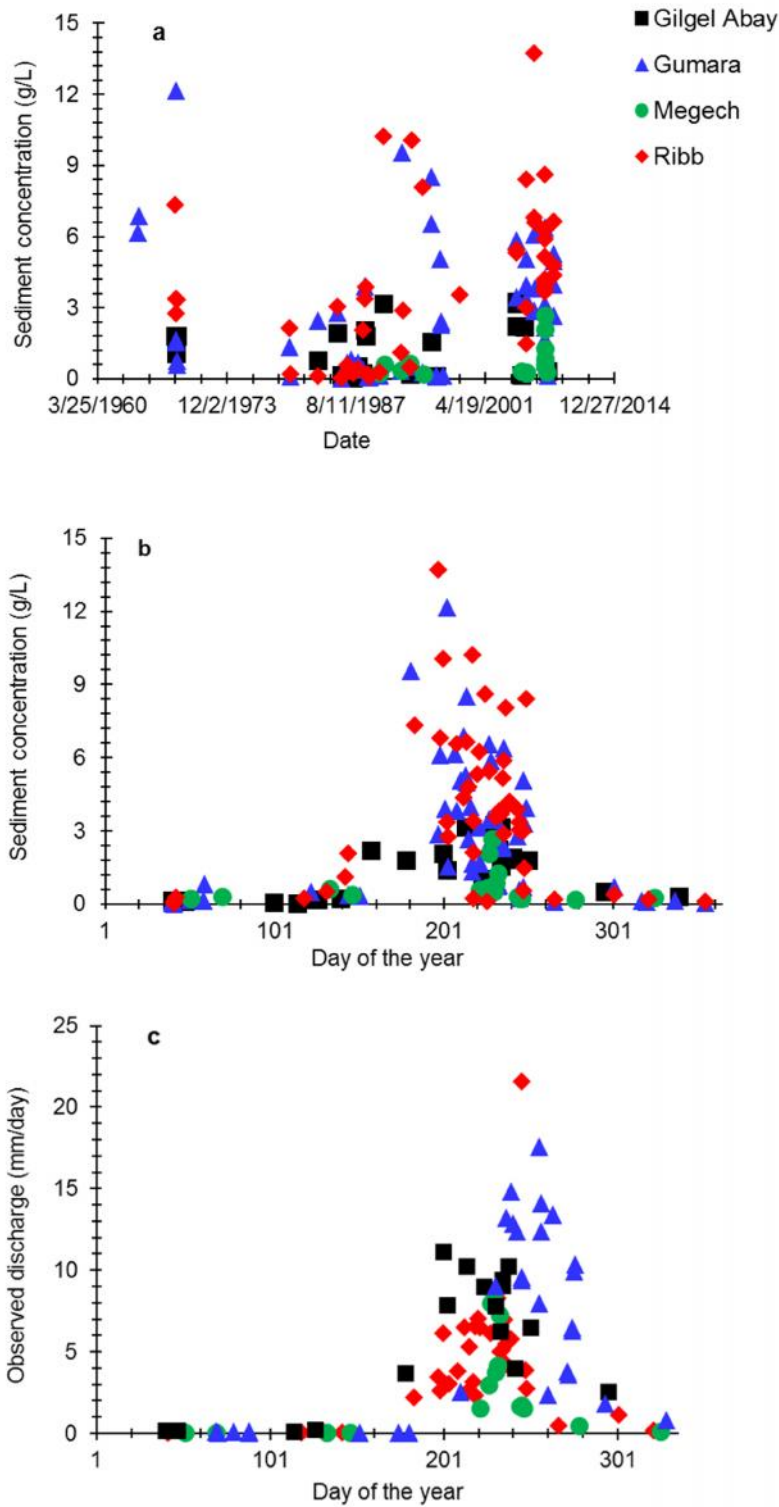
**Figures (revised)**



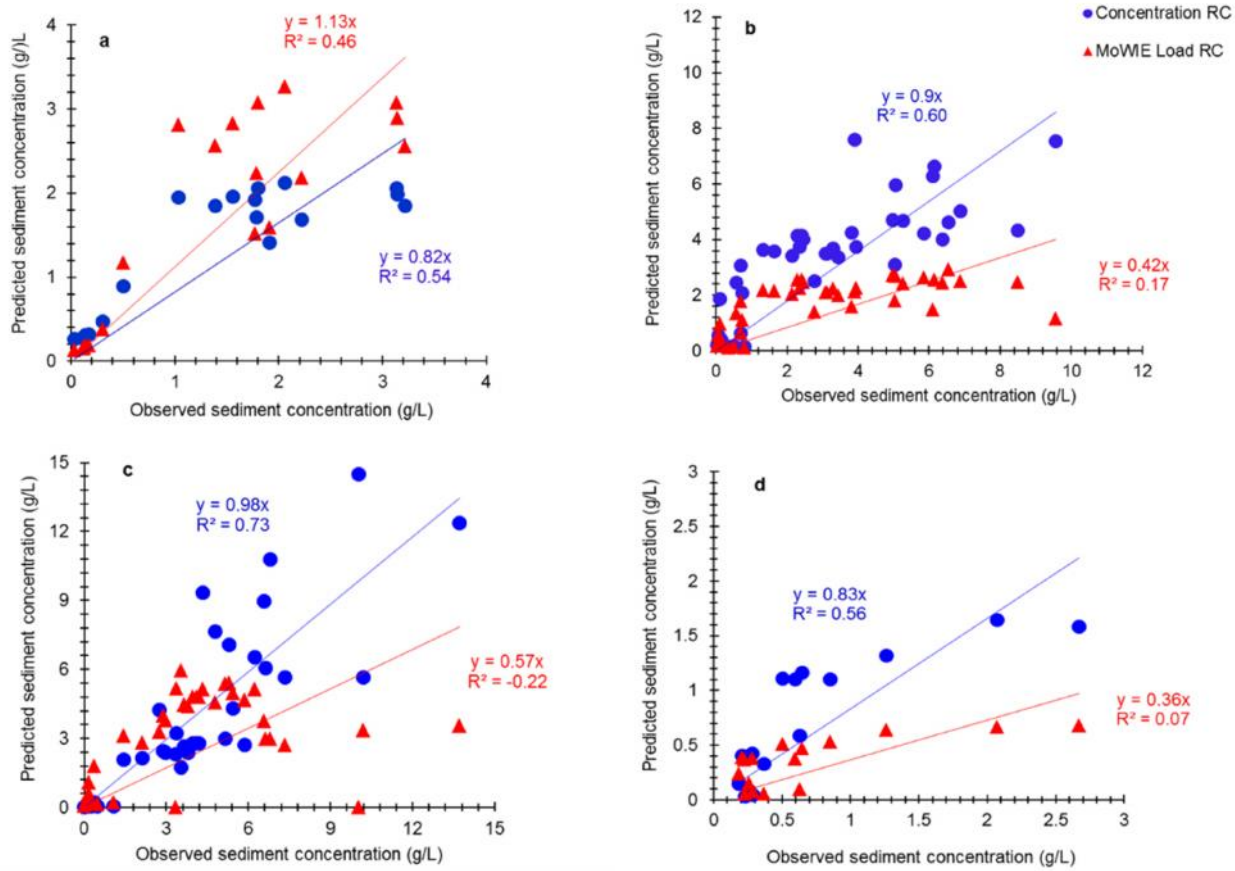
**Figure 1.** Relationship between sediment concentrations and cumulative effective rainfall.



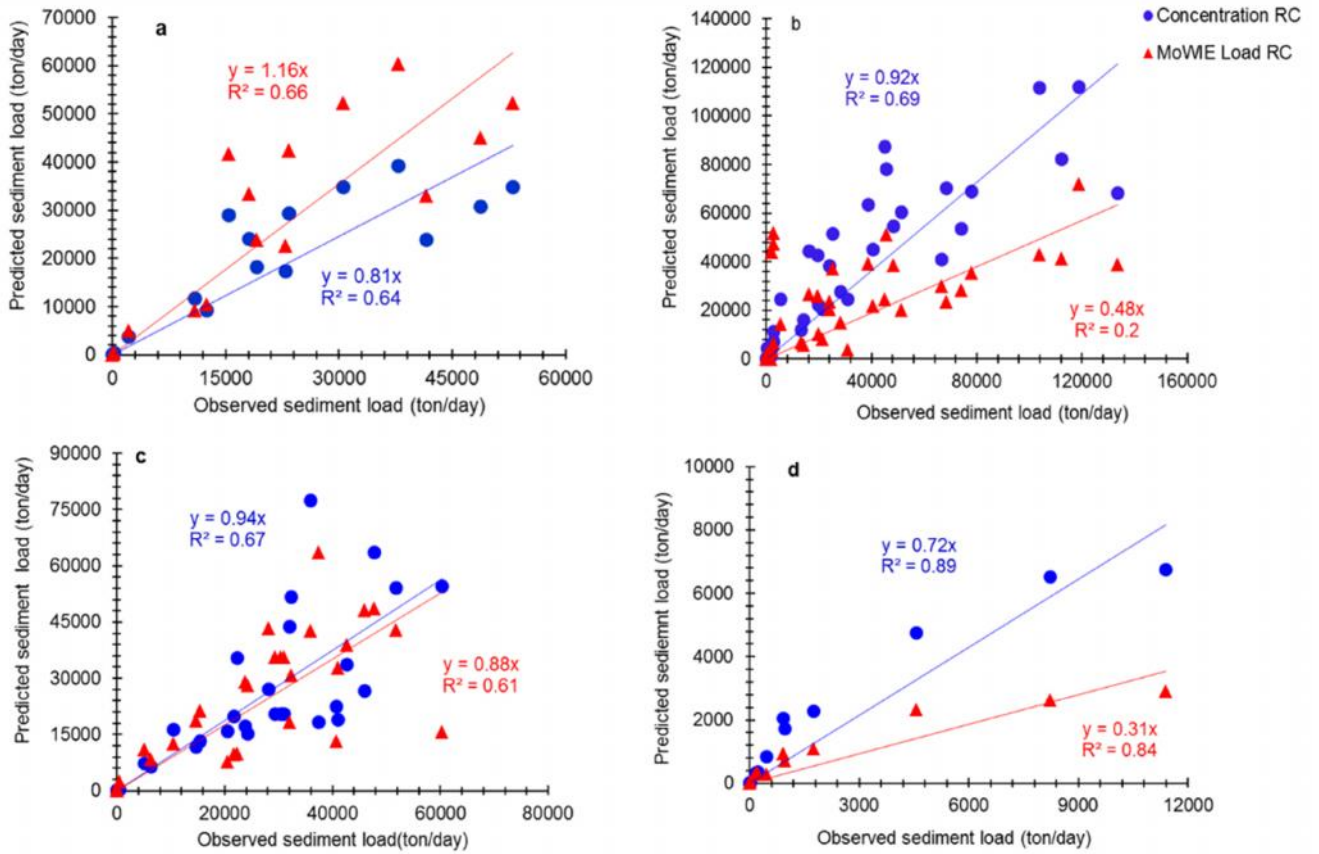
**Figure 2.** Location maps of the Lake Tana watersheds (Gilgel Abay, Gumara, Ribb and Megech) and 100-ha watersheds (Debre Mawi, Anjeni and Maybar) in or close to the Blue Nile Basin.



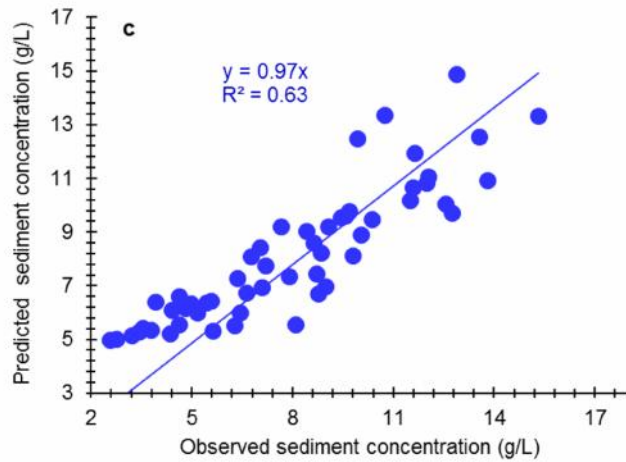
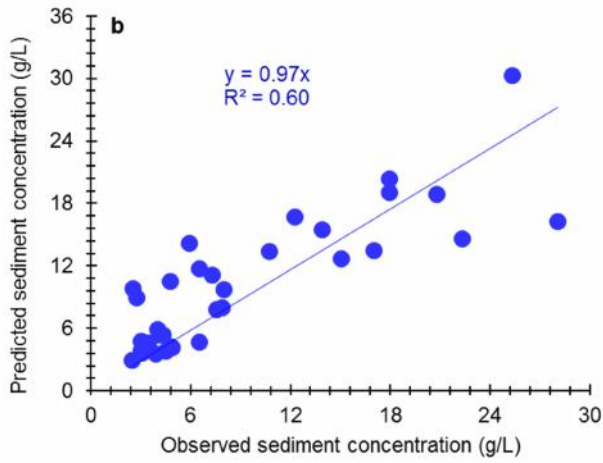
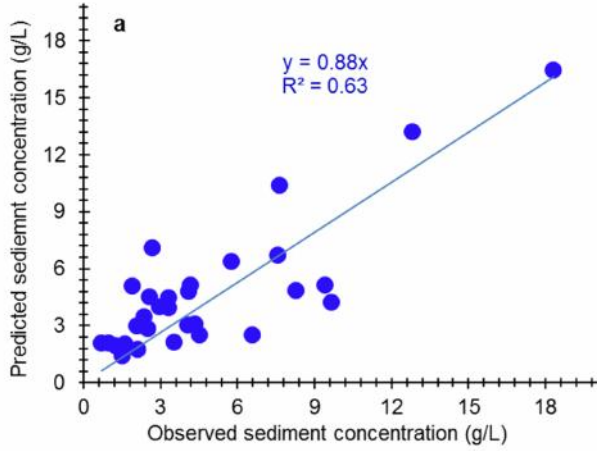
**Figure 3.** Observed sediment concentration and discharge for the four Lake Tana watersheds: Gilgel Abay, Gumara, Megech and Ribb. **a.** sediment concentration vs date of sampling **b.** sediment concentration as a function of day of sampling independent of the year, and **c.** observed discharge plotted vs sampling day.



**Figure 4.** Predicted versus observed sediment concentration using concentration rating curve and MoWIE load rating curve for the Lake Tana watersheds (a) Gilgel Abay, (b) Gumara, (c) Ribb, (d) Megech



**Figure 5.** Predicted versus observed sediment load using concentration rating curve and MoWIE load rating curve for the Lake Tana watersheds (a) Gilgel Abay, (b) Gumara, (c) Ribb, (d) Megech



**Figure 6.** Predicted and observed sediment concentration using concentration rating curve for the 100 ha watersheds (a) Maybar, (b) Debre Mawi and (c) Anjeni