

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

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Abstract

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

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

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

1 Introduction

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

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

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

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

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

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

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

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

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

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

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

The load rating curve Eq. (1) inherently assumes a unique relationship between discharge and concentration (i.e., a_c is constant, Gao, 2008). However when observed sediment 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. Zumr et al (2015) noted that sediment
21 transport originated from saturated 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.

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

2 THEORY: CONCENTRATION RATING CURVES

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

feeds the river, there will be small amount of sediments that the water picks up from the river bed or stirred up by animals or humans. Therefore, the sediment concentrations were calculated separately during the rainy monsoon phase and during the dry phase. Since the start of the rainy phase varies from year to year and from one location to another, we will use the cumulative effective rainfall, P_e , to replace the “time” parameter. P_e is determined by summing the daily effective rainfall which is equal to precipitation minus the potential evaporation for that day. The rainy phase starts when the cumulative effective rainfall, P_e is greater than 40 mm (from observation) and setting each time when P_e is negative to zero. As we will see later in most of the Lake Tana basin this occurs in the beginning of July , but it begins in mid-May in Gilgel Abay because the rainy phase starts earlier in a southern direction. For all of the watersheds the rainy phase ends the beginning of October

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

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

where a_s is sediment source limiting factor, a_t is the sediment transport limiting factor, P_e is the cumulative effective rainfall (mm) at a particular day, P_T is the threshold cumulative rainfall up to that amount the a_c parameter linearly decreases with cumulative rainfall, P_e , and after which the sediment concentration remains at the source limit. Thus, when P_e is equal to and greater than P_T , the ratio becomes one, which indicates that the sediment concentration is equal the source limit. The “ a_c ” and “ a_s ” parameters depends on a number of factors such as slope length, particle size and disposability. In addition, “ a_s ” parameter varies with the cohesion of the soil (Yu et al., 1997). The threshold value was found in other simulations to be around 600 mm (Tilahun et al., 2013 a, b). The values of all three

parameters are therefore difficult to predict a priori and need to be calibrated. As we will see hereafter they are in relatively narrow range indicating that they have some physical meaning.

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

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

For the dry monsoon phase the concentration is

$$C = a_b Q^{0.4} \quad (4b)$$

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

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

And for the dry monsoon M can be expressed as:

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

3 Materials and methods

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

3.1 Description of study areas

The 15,000 km² Lake Tana basin is in the headwaters of the approximately 180,000 km² Blue Nile basin. The average annual discharge from Lake Tana is 3.8×10^9 m³ (3.8 BCM) which is approximately 7% of that of the Blue Nile at the Ethiopian Sudanese border (Awulachew et al., 2009). The elevation in the basin ranges from 1787 m to 4260 m. The major rivers that contribute 93% of the inflow to the lake are Gilgel Abay, Rib, Gumara and Megech. The gaging stations are located 95, 20, 26 and 40 km, respectively, to the lake inlet as shown in Fig. 2. The three micro watersheds are Debre Mawi, Anjeni and Maybar. The 91ha Debre Mawi and the 113ha Anjeni are located in the Blue Nile basin south of Bahir Dar at 35 km and 220 km respectively. The 112ha Maybar is just located on the boundary of the Blue Nile Basin near Dessie 300 km east of Bahir Dar. Average annual rainfall for all watersheds in this study varies between 1100 to over 1900 mm yr⁻¹ (Table 1).

3.2 Available Data

3.2.1 Discharge and sediment concentrations

Irregular measured discharge and sediment concentration data by Ministry of Water Irrigation and Energy (MoWIE) for the major four rivers in Lake Tana basin were available

from 1964 to 2008. The numbers of observations available for the Lake Tana watersheds used for this analysis period were 23, 53, 52 and 16 for the Gilgel Abay, Gumara, Ribb and Megech watersheds, respectively. The data of the 100-ha watersheds were collected for Anjeni and Maybar by ARARI (Amhara Region Agricultural Research Institute). The Debre Mawi data were collected partly by ARARI and us and is described in Tilahun et al. (2013 a, b).

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

Climate data: Rainfall and temperature data for the Lake Tana watersheds (Table 1) were available from 1994 to 2008 by the National Metrological Agency of Ethiopia (NMAE), Bahir Dar branch. The areal rainfall was calculated by using Thiessen-polygon method for the available rainfall stations for the Lake Tana watersheds as these watersheds have two or more rainfall stations. The method was chosen because it is simple and does not require additional information. Details are given in the supplementary materials (Supplementary Material, Table A1). The Anjeni and Maybar precipitation and temperature measured in the watershed were made available by ARARI. The precipitation data for Debre Mawi was collected by us on site. To fill the missing data the gage at Adet (8 km

away) was used. Temperature was obtained for the Adet station from the Adet Agricultural Research Center.

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

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

3.3 Methods

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

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

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

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

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

3.4. Statistical analysis

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

4. RESULTS

4.1 Lake Tana watershed

4.1.1. Observed sediment concentration and load

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

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

4.1.2 Evaluation of sediment concentration predictions

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

For the Lake Tana watersheds, the sediment concentrations are under predicted by the MoWIE load rating curve and indicated poor prediction performance (Table 3, Fig 4). The concentration rating curve fits the concentrations satisfactory with Nash Sutcliffe values of 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 MoWIE load rating curves are poor in predicting concentrations.

4.1.3 Evaluation of sediment load predictions

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

4.2 Results of the three 100-ha watersheds

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

5. Discussion

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

5.1 Predicting sediment concentrations (Lake Tana watersheds)

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

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

5.2 Predicting sediment loads (Lake Tana watersheds)

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

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

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

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

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

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

There was a threefold difference in transport coefficients (Table 2, but independent of watershed area). It varies in the Lake Tana basin between 1.6 g/L⁻¹ (mm/day)^{-0.4} for the Gilgel Abay and 5.9 g/L⁻¹ (mm/day)^{-0.4} for the Gumara. The basic assumption in the concentration rating curve is that the sediment concentrations are determined by the transport capacity after land is plowed and rills are formed. Differences in the value for the transport coefficient can be related to the slope of the watershed since the transport coefficients are dependent on the stream power and the stream power is a function of slope (Gao 2008). The Gilgel Abay has 22% of land in the lowest slope category (0-2%) which is three times that in Ribb and Gumara. Moreover, the Gilgel Abay has only 1% in slope of greater than 30% while the other watershed have 9% or more in this category. Similarly Anjeni, in which most land is terraced, has gentle slope and small transport coefficient 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 catchment characteristics for the ungauged catchments for predicting
21 concentrations and load in the upper Blue Nile Basin.**

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1 REFERENCES

- 2
- 3 Ali, Y. S. A., Crosato, A., Mohamed, Y. A., Abdalla, S. H. & Wright, N. G. 2014. Sediment
4 balances in the Blue Nile River Basin. *International Journal of Sediment Research.*,
5 29,316-328, 2014.
- 6 [Arora, M., Kumar, R., Kumar, N., and Malhotra, J.: Assessment of suspended sediment
7 concentration and load from a large Himalayan glacier, *Hydrology Research*, 45,292-
8 306, 2014.](#)
- 9 Arnold, J. G., Srinivasan, R., Muttiah, R. S., and Williams, J. R. Large area hydrologic
10 modeling and assessment part I: Model development. *JAWRA Journal of the
11 American Water Resources Association*, 34, 73–89, 1998.
- 12 Asselman, N.E.M.: Suspended sediment dynamics in a large basin: the River Rhine.
13 *Hydrological Processes*, 13, 1437-1450,1999.
- 14 Asselman, N.E.M., Fitting and interpretation of sediment rating curves. *Journal of
15 Hydrology*, 234, 228–248, 2000
- 16 Awulachew, S.B., McCartney, M., Steenhuis, T.S., and Ahmed, A. A.: A review of
17 hydrology, sediment and water resource use in the Blue Nile Basin, *International
18 Water Mangement Institute (IWMI)*, 131,pp 81,2009.
- 19 [Ayana, E.K., Philpot, W.and T.S Steenhuis. Evaluating suitability of modis-terra images for
20 reproducing historic sediment concentrations in water bodies: Lake Tana, Ethiopia
21 *International Journal of Applied Earth Observations and Geoinformation* 26: 286-297,
22 2014.](#)
- 23 Ciesiolka, C.A., Coughlan, K.J., Rose, C.W., Escalante, M.C., Hashim, G.M., Paningbatan,
24 E.P., and Sombatpanit, S.: Methodology for a multi-country study of soil erosion
25 management, *Soil Technology*, 8, 179–192, 1995.
- 26 [Choi, S.U., and Lee, J.: Assessment of total sediment load in rivers using lateral distribution
27 method, *Journal of Hydro-Environment Research*, 9,381-387, DOI:
28 10.1016/j.jher.2014.06.002, 2015.](#)

- Dagnew, D. C., Guzman, C. D., Zegeye, A. D., Tibebu, T. Y., Getaneh, M., Abate, S., Zemale, F. A., Ayana, E. K., Tilahun, S. A., and Steenhuis, T. S.: Impact of conservation practices on runoff and soil loss in the sub-humid Ethiopian Highlands: The Debre Mawi watershed. *Journal of Hydro. Hydromech.*, 63, DOI: 10.1515/johh-2015-002, 2015.
- Easton, Z.M., Fuka, D.R., White, E.D., Collick, A.S., Biruk, A.B., McCartney, M., Awulachew, S.B., Ahmed, A.A., and Steenhuis, T.S.: A multi basin SWAT model analysis of runoff and sedimentation in the Blue Nile, Ethiopia, *Hydrological and Earth System Science*, 14: pp.1827-1841, doi:10.5194/hess-14-1827-2010, 2010.
- Enku, T.E., and Melesse, A.M.: A Simple Temperature Method for the Estimation of Evapotranspiration. *Hydrological Processes* 28, 2945–2960, 2014.
- Fenn, C. R., Gurnell, A. M., and Beecroft, I. R.: An Evaluation of the Use of Suspended Sediment Rating Curves for the Prediction of Suspended Sediment Concentration in a Proglacial Stream, *Geografiska Annaler, Series A Physical Geography*, 67, 71-82, 1985.
- Foster, G., and Meyer, L.: Mathematical simulation of upland erosion by fundamental erosion mechanics, Present and prospective technology for predicting sediment yields and sources, US Department of Agriculture, Washington, DC, 1975.
- Gao, P.: Understanding watershed suspended sediment transport, *Progress in Physical Geography*, 32, 243-264, 2008.
- Guzman, C.D., Tilahun, S.A., Zegeye, A. D., and Steenhuis, T. S.: Suspended sediment concentration–discharge relationships in the (sub-) humid Ethiopian highlands. *Hydrological Earth Systems Science*, 17, 1067–1077, 2013.
- Haile, M., Herweg, K., and Stillhardt, B.: Sustainable land management – a new approach to soil and water conservation in Ethiopia, Land Resource Management and Environmental Protection Department, Mekelle University, Mekelle, Ethiopia, Center for Development and Environment (CDE), University of Bern and Swiss National Center of Competence in Research (NCCR) North-South, Bern, Switzerland, pp. 269, 2006.

- Hairsine, P. B., and Rose, C. W.: Modeling water erosion due to overland flow using Physical principles 1. Sheet flow, *Water Resource Research*, 28, 237–243, 1992.
- Hydrologic Engineering Center.: Flow Transitions in Bridge Backwater Analysis, U.S. Army Corps of Engineers, Davis, CA, pp.71, 1995
- Henck, A. C., Montgomery, D. R., Huntington, K. W., and Liang, C.: Monsoon control of effective discharge, Yunnan and Tibet. *Geology*, 38, 975-978, 2010.
- Horowitz, A. J.: A quarter century of declining suspended sediment fluxes in the Mississippi River and the effect of the 1993 flood. *Hydrological Processes*, 24, 13-34, 2010.
- Irvine, K. N., and Drake, J. J.: Process-Oriented Estimation of Suspended Sediment Concentration, *JAWRA Journal of the American Water Bulletin*, 23, 1017- 1025, 1987.
- Jones, C., Dyke, P., Williams, J., Kiniry, J., Benson, V., and Griggs, R.: EPIC: an operational model for evaluation of agricultural sustainability. *Agricultural Systems*, 37, 341-350, 1991.
- Kheirfam, H., and Vafakhah M.: Assessment of some homogeneous methods for the regional analysis of suspended sediment yield in the south and southeast of the Caspian Sea, *Journal Of Earth System Science*, 124, 1247-1263, DOI: 10.1007/s12040-015-0604-7, 2015.
- Knisel, W.G.: CREAMS. A field-scale model for chemicals, runoff and erosion from agricultural management systems. USDA Conservation Research Report, 640 pp. 1980.
- Kokpinar, M. A., Altan-Sakarya, A. B., Kumcu, S. Y. , and Gogus, M.: Assessment of sediment yield estimations for large watershed areas: a case study for the Seyhan, Demirkopru and Hirfanli reservoirs in Turkey, *Hydrological Sciences Journal*, 60, 2189-2203, DOI: 10.1080/02626667.2014.959954, 2015.
- Masoumeh R. and Mehdi F.: Estimating Suspended sediment concentration by a neural differential evolution (NDE) and comparison to ANFIS and three ANN Models, *Disaster advances*, 5, 346-359, 2012

- 1 Miller, C. R.: Analysis of flow-duration, sediment-rating curve method of computing
2 sediment yield. Denver: US Bureau of Reclamation. 55 pp., 1951.
- 3 Moriasi, D., Arnold, J., Van, L.M., Bingner, R., Harmel, R., and Veith T.: Model evaluation
4 guidelines for systematic quantification of accuracy in watershed simulations.
5 Transactions of the American Society of Agricultural and Biological Engineers, 50,
6 885-900, 2007.
- 7 Mueller, G., and Foerstner, U.: General relationship between suspended sediment
8 Concentrations and water discharge in the Alpenrhein and some other rivers. Nature,
9 217, 244- 245, 1968.
- 10 Nearing, M., Foster, G., Lane, L. and Finkner, S.: A process-based soil erosion model for
11 USDA-Water Erosion Prediction Project technology, Transactions of the American
12 Society of Agricultural and Biological Engineers, 32, 1587-1593, 1989.
- 13 Nyssen, J., Poesen, J., Moeyersons, J., Deckers, J., Haile, M., and Lang, A.: Human
14 impact on the environment in the Ethiopian and Eritrean Highlands—a state of the
15 art, Earth Science Review, 64, 273–320, 2004.
- 16 Özgür K.: Development of Stream flow-Suspended Sediment Rating Curve Using a range
17 dependent neural network, International Journal of Science and Technology, 2, 49-
18 61, 2007.
- 19 Phillips, J.M., Webb, B.W., Walling, D.E., Leeks, G.J.L.: Estimating the suspended
20 sediment loads of rivers in the LOIS study area using infrequent samples.
21 Hydrological Processes, 13, 1035-1050, 1999.
- 22 Renard, K.G., Foster, G. R., Wessies, D. K., and Yoder, D. C.: Prediction of soil erosion by
23 water: A guide to conservation planning with the Revised Universal Soil Loss
24 Equation (RUSLE). Report ARS 703, Agricultural Research Service, US Department
25 of Agriculture, 1991.
- 26 Setegn, S.G., Srinivasan, R., Dargahi, B., and Melesse, A. M.: Spatial delineation of soil
27 erosion vulnerability in the Lake Tana Basin, Ethiopia, Hydrological Processes,
28 23(26): 3738-3750, DOI: 10.1002/hyp.7476, 2009.

- 1 [Sichingabula, H. M.: Factors controlling variations in suspended sediment concentration for](#)
2 [single-valued sediment rating curves, Fraser River, British Columbia, Canada By:](#)
3 [Hydrological Processes, 12, 1869-1894, 1998.](#)
- 4 Steenhuis, T.S., A.S. Collick, Z. M. Easton, E.S. Leggesse, H. K. Bayabil, E. D. White,
5 S.B. Awulachew, E. Adgo, A.A. Ahmed.: Predicting Discharge and Erosion for the
6 Abay (Blue Nile) with a simple model, *Hydrological Processes*, 23: 3728–3737,
7 2009.
- 8 [Sun, H., Cornish, P. S., and Daniell, T. M.: Turbidity-based erosion estimation in a](#)
9 [catchment in South Australia By: *Journal of Hydrology*, 253, 227-238, DOI:](#)
10 [10.1016/S0022-1694\(01\)00475-9, 2001.](#)
- 11 Tebebu, T.Y., Abiy, A.Z., Dahlke, H.E., Easton, Z.M., Zegeye, A.D., Tilahun, S.A., Collick,
12 A.S., Kidnau, S., Moges, S., and Dadgari, F. and Steenhuis. T.S.: Surface and
13 subsurface flow effect on permanent gully formation and upland erosion near Lake
14 Tana in the northern highlands of Ethiopia, *Hydrological and Earth System Science*,
15 14, 2207–2217, doi:10.5194/hess-14-2207-2010, 2010.
- 16 Tilahun, S.A.: Observations and Modeling of Erosion from spatially and Temporally
17 Distributed sources in the (semi)Humid Ethiopian Highlands, A dissertation
18 presented to the Faculty of the Graduate School of Cornell University, in partial
19 fulfillment of the requirements for the Degree of Doctor of Philosophy, New York,
20 USA,39-67, 2012.
- 21 Tilahun S.A., Mukundan, R., Demisse, B.A., Engda, T.A., Guzman, C.D., Tarakegn, B.C.,
22 Easton, Z.M., Collick, A.S., Zegeye, A.D., Schneiderman, E.M., Parlange J.Y., and
23 Steenhuis T.S.: A Saturation Excess Erosion Model. *Transactions of the American*
24 *Society of Agricultural and Biological Engineers*, 56: 681-695, 2013a.
- 25 Tilahun SA, Guzman CD, Zegeye AD, Ayana EK, Collick AS, Yitaferu B, Steenhuis T.S.:
26 Spatial and Temporal Patterns of Soil Erosion in the Semi-humid Ethiopian
27 Highlands: A Case Study of Debre Mawi Watershed. In *Nile River Basin:*
28 *Ecohydrological Challenges, Climate Change and Hydropolitics*, 149-163. Melesse
29 A.M. et al., ed. Springer International Publishing Switzerland, 2013b.

- 1 Tilahun S. A., Guzman C. D., Zegeye A. D., Engda T. A., Collick A.S., Rimmer A., and
2 Steenhuis T. S.: An efficient semi-distributed hillslope erosion model for the sub
3 humid Ethiopian Highlands. *Hydrol. Earth Syst. Sci.*, 17, 1051–1063, 2013c.
- 4 Tilahun, S. A., Guzman, C. D., Zegeye, A. D., Dagnaw, D. C., Collick, A. S., Yitaferu, B. and
5 Steenhuis, T. S.: Distributed discharge and sediment concentration predictions in the
6 sub-humid Ethiopian highlands: the Debre Mawi watershed, *Hydrological Processes*,
7 29, 1817-1828, 2015.
- 8 Vanmaercke, M., Zenebe, A., Poesen, J., Nyssen, J., Vertstraeten, G., and Deckers, J.
9 Sediment dynamics and the role of flash floods in sediment export from medium-
10 sized catchments: a case study from the semi-arid tropical highlands in northern
11 Ethiopia, *Journal of Soil Sediment*, 10, 611-627, 2010
- 12 Vijverberg, J., Dejen, E., Getahun, A. and Nagelkerke, L. A.: The composition of fish
13 communities of nine Ethiopian lakes along a north-south gradient: threats and
14 possible solutions, *Animal Biology*, 62, 191pp., 2012.
- 15 Walling, D. E.: Assessing the accuracy of suspended sediment rating curves for a small
16 basin, *Water Resource Research*, 13, 531- 538, 1977.
- 17 Williams, J. R. and Berndt, H. D.: Sediment yield prediction based on watershed hydrology.
18 *Trans. Am. Soc. Agric. Engrs*, 20, 1100–1104, 1977
- 19 Wischmeier W.H., and Smith D.D.: Predicting rainfall-erosion losses from cropland east of
20 the Rocky Mountains. *Agriculture Handbook*, 282 pp., USDA-ARS,1965.
- 21 Young, R. A., Onstad, C., Bosch, D. & Anderson, W., Agnps: A nonpoint-source pollution
22 model for evaluating agricultural watersheds, *Journal of soil and water conservation*,
23 44, 168-173, 1989.
- 24
- 25 Yu, B., Rose, C. W., Ciesiolka, C. A., Coughlan, K. J., and Fentie, B.: Toward a framework
26 for Runoff and soil loss prediction using GUEST technology, *Australian Journal of*
27 *Soil Research*, 35, 1191–1212, 1997.
- 28
- 29 Zegeye, A.D., Steenhuis, T.S., Blake, R.W., Kidnau, S., Collick A.S., and F. Dadgari.:
30 Assessment of Upland Erosion Processes and Farmer Perception of Land

conservation in Debre Mawi Watershed, near Lake Tana, Ethiopia, *Ecohydrology and Hydrobiology*, 10, 297-306, 2010.

Zumr, D Dostal, and T Devaty, J., Identification of prevailing storm runoff generation mechanisms in an intensively cultivated catchment. *Journal of Hydrology and Hydromechanics* 63: 246-254, 2015

SUPPLEMENTARY MATERIAL

Table A1: Theissen weight derived from the Theissen 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 ²)	Mean Annual Rainfall(mm)	Rating curve (Eq.1) by MoWIE* load Rating Curve(RC) constants	
Lake Tana watersheds			a	b
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) ^{-0.4})		a factor for base flow (a_b) (g/l (mm/day) ^{-0.4})	Threshold effective precipitation (mm)	The date where the a_s starts
	a_t	a_s	a_b	P_T	
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 ²	NS	R ²
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 ²	NS	R ²
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

List of Figures Revised

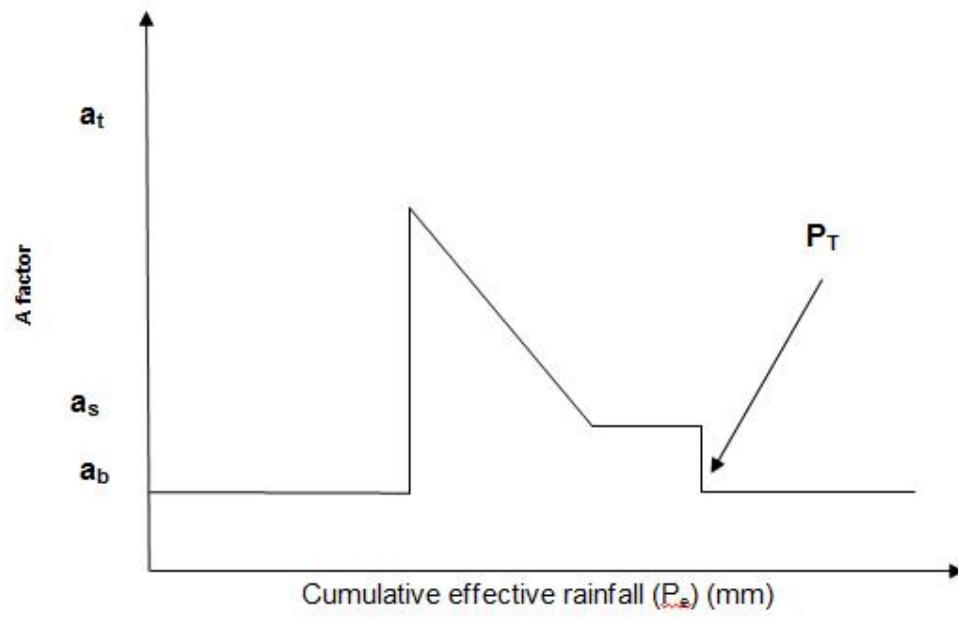


Figure 1. Relationship between sediment concentrations and cumulative effective rainfall.

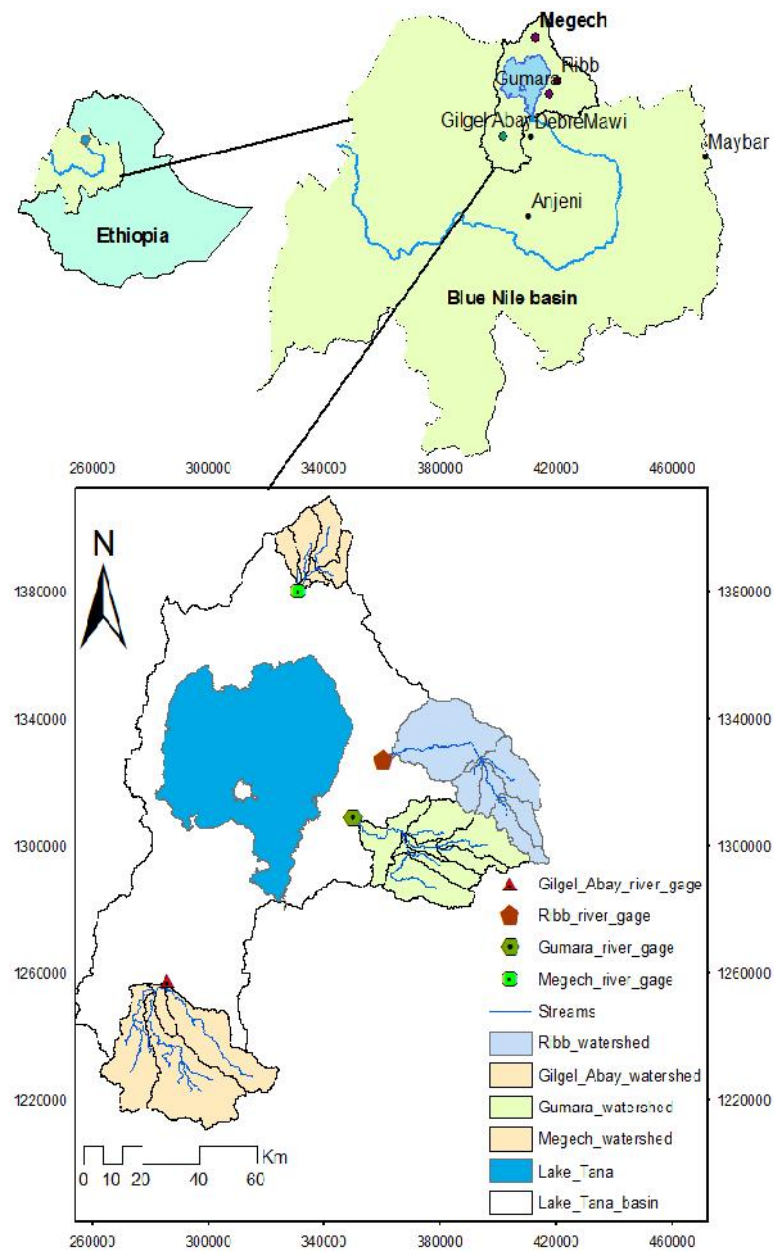
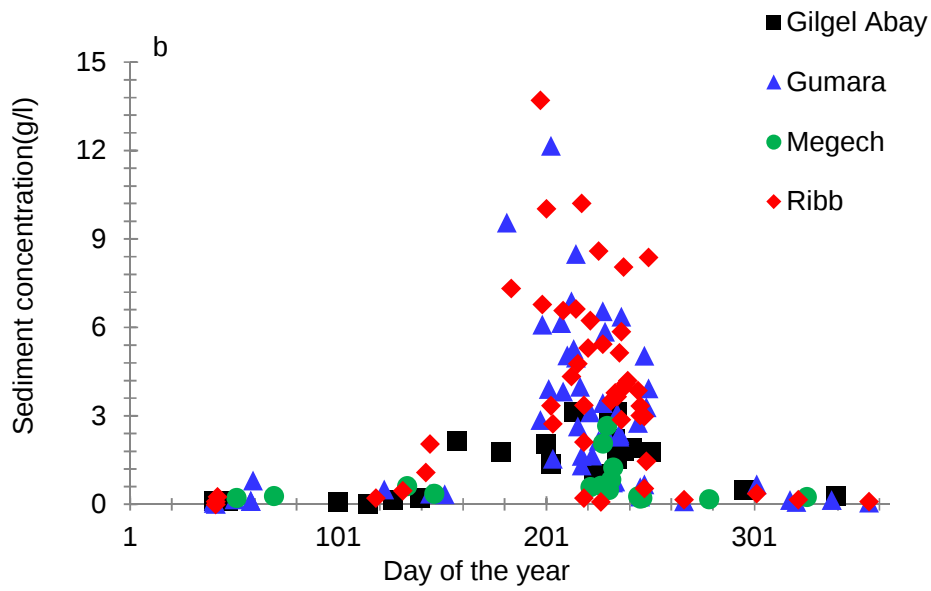
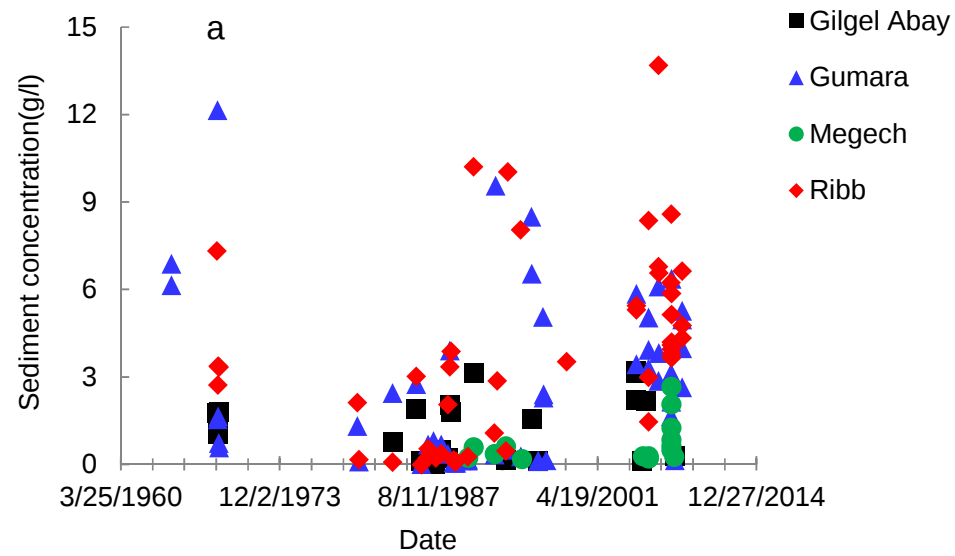


Figure 2. Location maps of the **Lake Tana watersheds** (Gilgel Abay, Gumara, Ribb and Megech) and 100-ha watersheds (Debre Mawi, Anjeni and Maybar) in or close to the Blue Nile Basin.



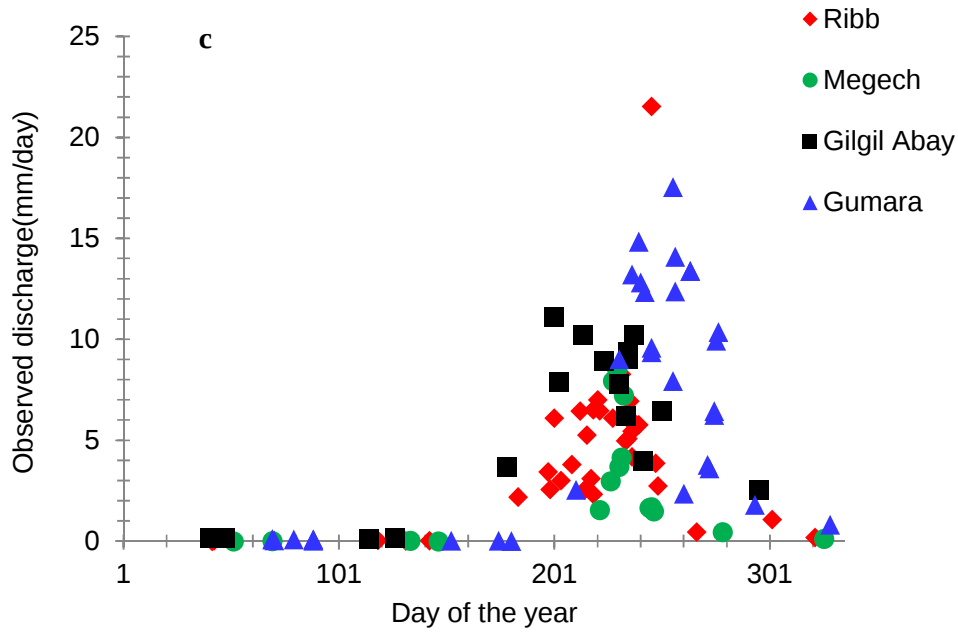
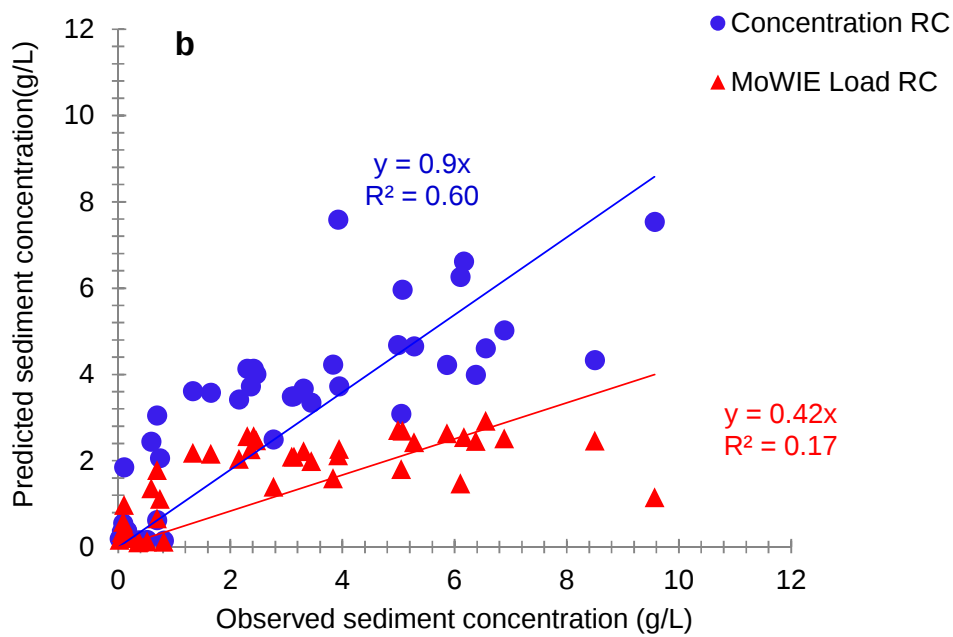
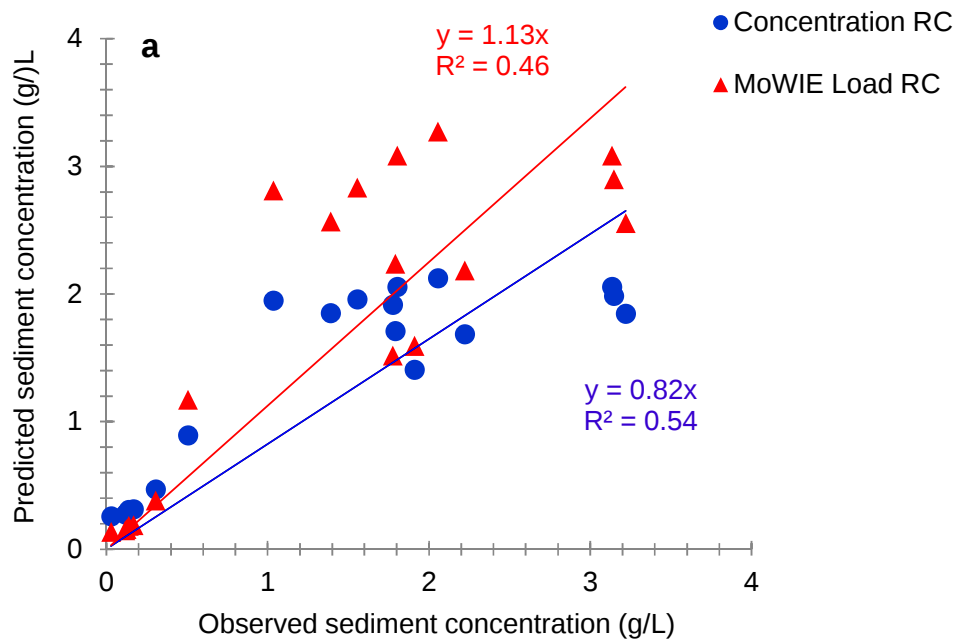


Figure 3. Observed sediment concentration and discharge for the four Lake Tana watersheds: Gilgel Abay, Gumara, Megech and Ribb. **a.** sediment concentration vs date of sampling **b.** sediment concentration as a function of day of sampling independent of the year, and **c.** observed discharge plotted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



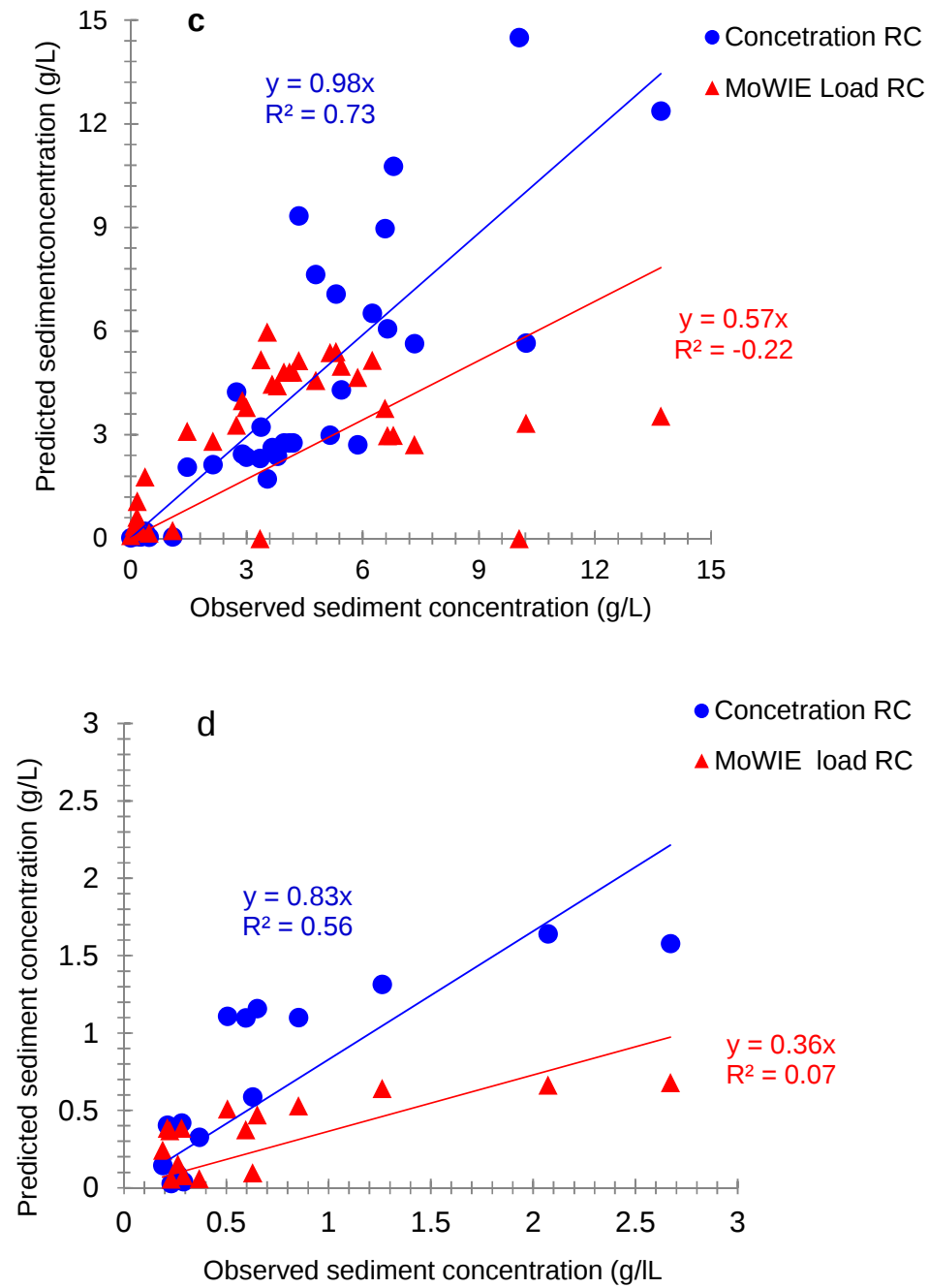
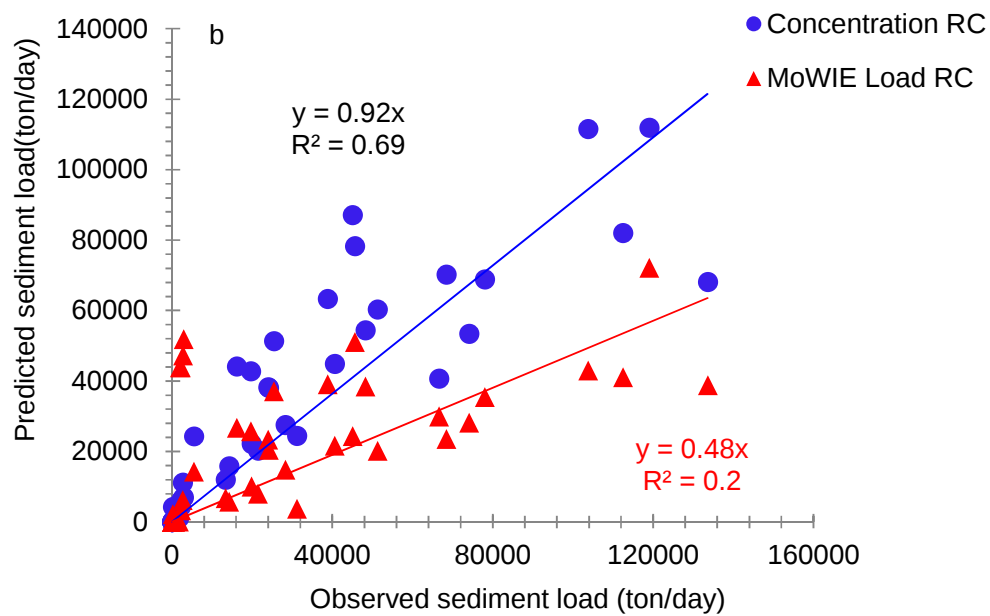
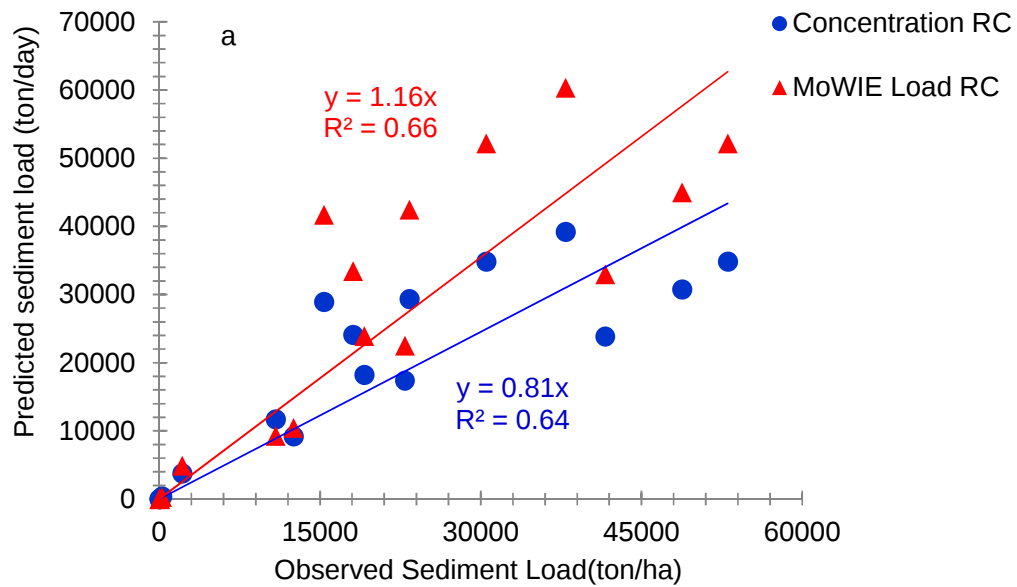


Figure 4. Predicted versus observed sediment concentration using concentration rating curve and MoWIE load rating curve for the Lake Tana watersheds (a) Gilgel Abay, (b) Gumara, (c) Ribb, (d) Megech



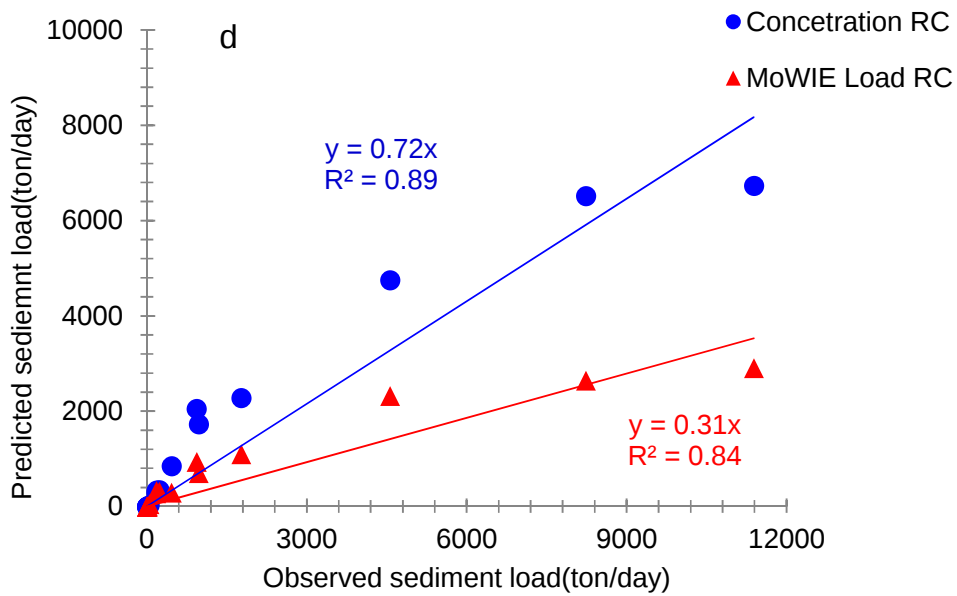
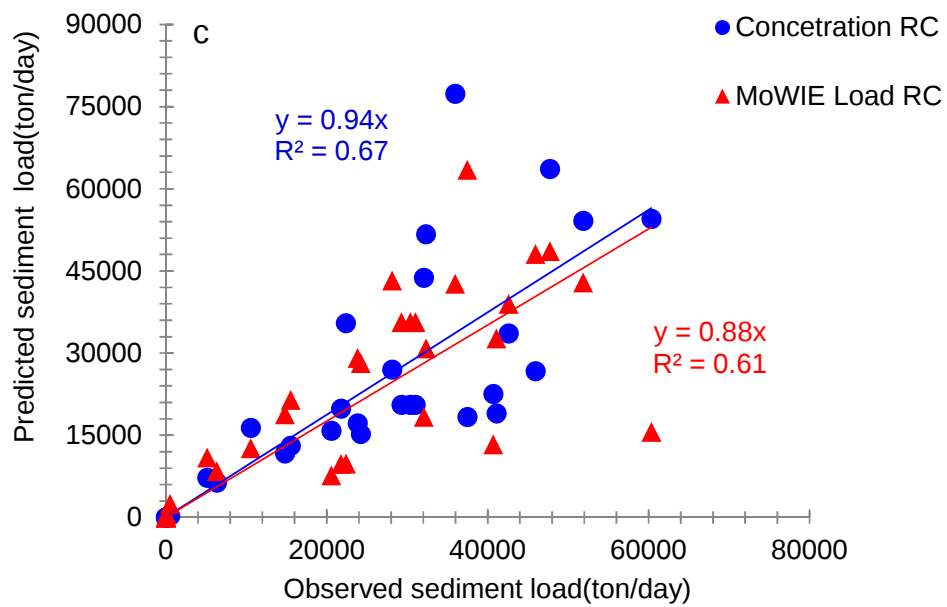
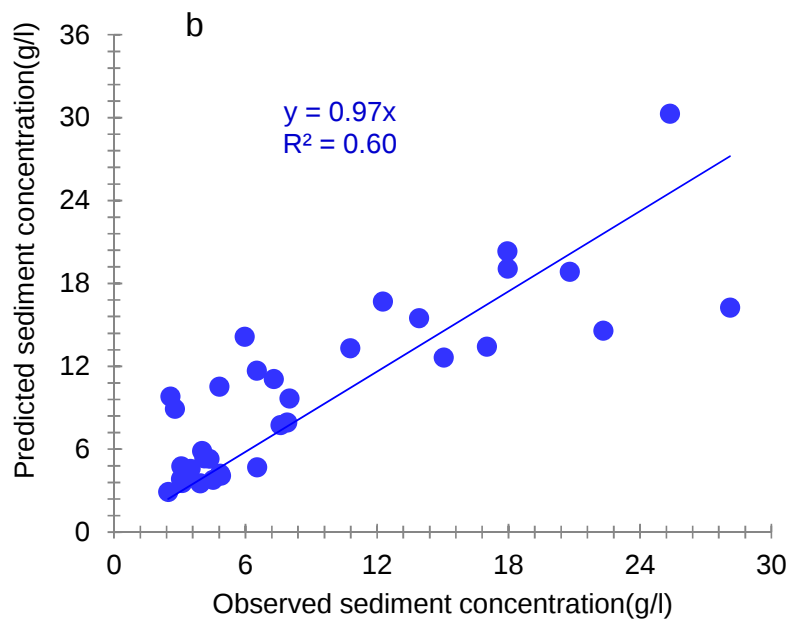
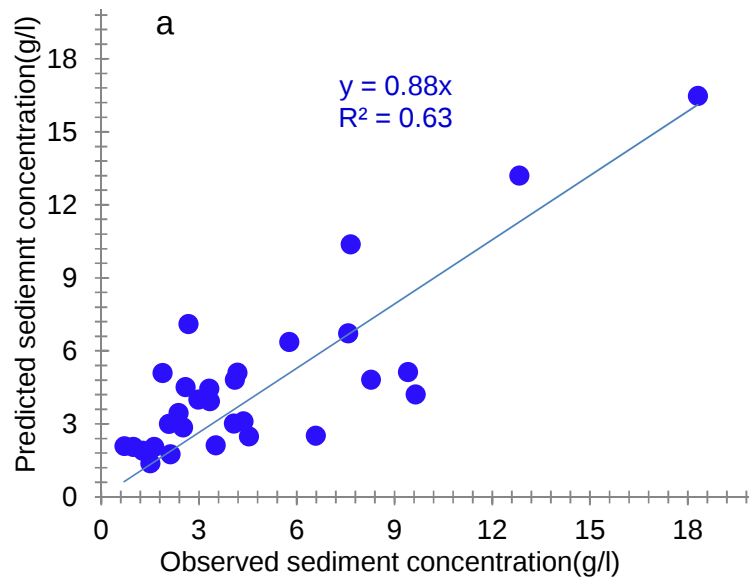


Figure 5. Predicted versus observed sediment load using concentration rating curve and MoWIE load rating curve for the Lake Tana watersheds (a) Gilgel Abay, (b) Gumara, (c) Ribb, (d) Megech



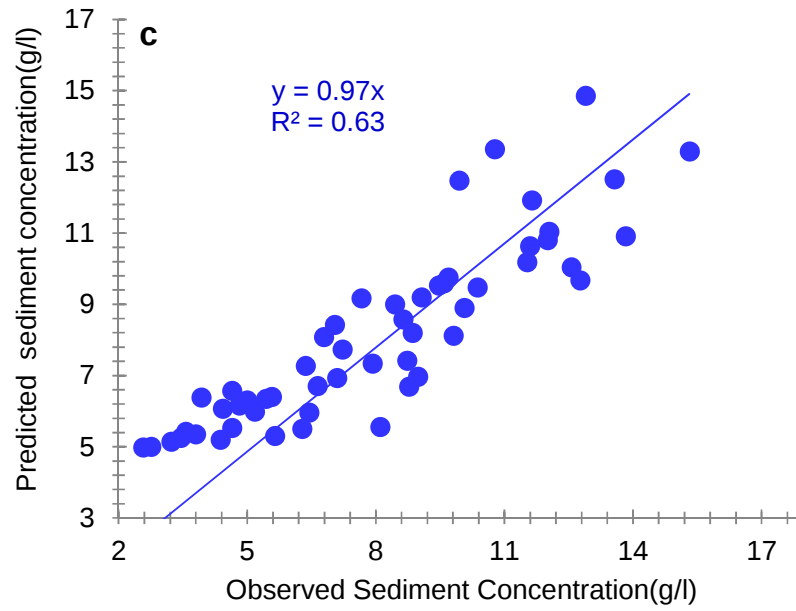


Figure 6. Predicted and observed sediment concentration using concentration rating curve for the 100 ha watersheds (a) Maybar, (b) Debre Mawi and (c) Anjeni