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Sediment concentration rating curves for a monsoonal climate: upper Blue Nile Basin

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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 discontinuous 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 100-ha 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.

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. To determine sediment loads in the absence of these measurements, models have been developed and rating curves have been used. Knowing the total sediment loads of rivers is essential in the evaluation of siltation of reservoirs (Ali et al., 2014) and assessment of soil erosion and nutrient loss (Walling, 1977). Knowledge of sediment concentration is important in most environmental applications because among others they hamper fish reproduction and reduce the esthetic value of lakes and rivers (Vijverberg et al., 2012).

In the Blue Nile Basin in the Ethiopian highlands, where the construction of the Grand Ethiopian Renaissance Dam (GERD) is underway near the border of Sudan and planning for other hydroelectric dams upstream of it, 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 concentration and load to the lakes and man-made reservoir has become important.

Modeling sediment loss is fraught with difficulties unlike runoff that is bounded by the amount of rainfall; there is no upper bound for sediment load in the absence of data. The models most commonly used for predicting soil loss are the Universal Soil Loss of Equation and its derivates (USLE and MUSLE; Wischmeier and Smith, 1965). Hydrologic Engineering Center River Analysis System, (HEC-RAS, HEC 1995), Water Erosion Prediction Technology (WEPP, Nearing et al., 1989), Agricultural Non-Point Source Polution (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)

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Models (Masoumeh and Mehdi, 2012; Özgür, 2007). However, it is cumbersome to obtain the required data for these models especially in developing countries. Therefore, historically when concurrent concentration and discharge measurement are taken at irregular intervals; rating curves are often the preferred choice for predicting sediment loads (Horowitz, 2010).

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, 2010),

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

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,

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

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

Various reasons are given for the decrease in concentration with the progression of the rainy phase: Tilahun et al. (2013b) poses that with the progression of the rainy phase of the monsoon the value of $a_c$is a function of the portion of the area of newly plowed land which is initially high and then decreases during the rainy phase when the soil becomes wet and more cohesive. Nyssen et al. (2004), Vanmaercke et al. (2010), and Asselman (1999) showed that the sediment concentration depends on the sediment available for transport by runoff. Haile et al. (2006) and Awulachew et al. (2009) relate sediment concentration to the amount of plant cover protection which is increasing towards the end of the rainy period. However, Tebebu et al. (2010) noted that plant cover and sediment concentration were not statistically related. Zegeye et al. (2010) and Tilahun et al. (2013c) attributed the decreased loading with the cessation of the rill formations. In addition, the base flow increase 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 constant throughout the rainy season, this method cannot be used in environmental applications where the sediment concentration matters. The objective of this paper is, therefore, finding a realistic method in determining the decreasing sediment concentration with the progression of the monsoon using the limited data that is available in most of the tropics. The study is carried out in the Ethiopian highlands where four major rivers and their watersheds are selected in the Lake Tana basin and to test how well the relation performs for a range of scales, three small well monitored 100 ha watersheds were chosen in the humid highlands.

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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 ploughed 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 ploughed 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. We will, therefore, calculate the sediment concentration separately during the rainy monsoon phase and during the dry phase. 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 of May in Gilgel Abay because the rainy phase starts earlier in a southern direction. Mainly in all of the watersheds the rainy phase ends in the beginning of October.

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

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

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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 after where the sediment concentration is at the source limit. 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" parameter depends on a number of factors such as slope length, particle size and disposability (Yu et al., 1997)

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 Eqs. (2) and (3), the modified concentration rating curve can be written for the rainy phase as:

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

For the dry monsoon phase the concentration is

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

The load can be obtained with concentration rating curve can by multiplying Eq. (4) by Q.

For the rainy phase the load, M can be expressed as:

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

And for the dry monsoon phase M can be expressed as:

$$M = a_b Q^{1.4} \tag{5b}$$

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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". Selected three small (approximately 100 ha) watersheds are used for the assessment of scale effects in the concentration rating curve: Anjeni, Debre Mawi and Maybar. We will call these hereafter as "100 ha watersheds".

3.1 Description of study areas

The 15 000 km^2 Lake Tana basin is in the headwaters of the approximately 180 000 km^2 Blue Nile basin. The average annual discharge from Lake Tana is 3.8×10^9 m^3 (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 to 4260 m. The major rivers that contribute 93 % of the inflow to the lake are Gilgel Abay, Rib, Gumara and Megech. The gauging 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 91 ha Debre Mawi and the 113 ha Anjeni are located in the Blue Nile basin south of Bahir Dar at 35 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 1200 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 Electricity (MoWIE) for the major four rivers in Lake Tana basin were available for the period between 1964 to 2008. The numbers of observations available

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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 was collected partly by ARARI and us and is described in Tilahun et al. (2013a, b).

The sediment concentrations in the Lake Tana watershed has been increasing since the initial measurement were made in 1964. We selected the following periods for analysis 1968–2008 for Gilgel Abay, Gumara and Rib. For Megech the data was only available for 1990–2007 and the analysis was made with this data. We chose the years for the Anjeni (1996) and Maybar (1994) in which the soil and water conservation practices were established and installed in the second half of 1980's and the data were of good quality. For the Debre Mawi watershed the data in the years 2010 and 2011 were used before 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 (especially for the Lake Tana watersheds as these watersheds have two rainfall stations) details are given in the supplementary materials (Supplement, 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. The rainy phase in the study area started between May 15 and June 15(Table 2).

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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_l. These are listed in Table 1.

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 the 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 (2012) 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.

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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 all cases not more than 5 % of the total numbers of 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).

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 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 form 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

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increase at the end of May to the middle of June(Table 2).The maximum concentration occur 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 Eqs. (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 in addition not very well (Fig. 4). The concentration rating curve fits the concentrations relatively well with Nash Sutcliff values of 0.46 to 0.61 and R^2 values of 0.54 to 0.73 of with slopes close to one.

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. 6 and the goodness of fit in Table 4. The sediment loads (Fig. 6) are predicted satisfactorily with the MoWIE load rating curve for Gilgel Abay, Ribb and Megech with R^2 values ranging from 0.61–0.84 (Fig. 6).However unlike the concentration rating curve, 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. 6).

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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 Eqs. (3) and (4) gave a reasonably good fit with the observed values (Fig. 5) with R^2 values ranging from 0.56 to 0.69 (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 can 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 concentration were reasonably the same during the rainy phase (Fig. 3b, black dots).

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5.2 Predicting sediment loads (Lake Tana watersheds)

For the Lake Tana watersheds in the Ethiopia highlands, the concentration rating curve (Eq. 4) fitted the observed sediment loads more accurately than the MoWIE load rating curve (Eq. 1) as shown in Fig. 6. The only exception was the sediment load predictions for the Gilgel Abay (Fig. 6a) that was slightly better predicted by the MoWIE load curve than the concentration rating curves. Of course, 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. 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 loads and discharge. To demonstrate that the MoWIE log rating curve fits the log transformed values well we re-plotted Fig. 6b in the auxiliary material (Supplement, 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. 6b).

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

All fitting parameters for the concentration rating curve were remarkably 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 after which the concentration became independent of the rainfall (i.e., Eq. 5) varied between 561 mm yr^{-1} for the Gilgel Abay and 599 mm yr^{-1} for the Debre Mawi watershed. The difference among these values in all watersheds was significant.

In further discussion of the sediment transport parameters we will exclude the Megech since the gauge station is located below the reservoir. Sediment is deposited in the reservoir and the parameters are not representative of the watershed that is sub-

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ject to heavy gullying. For the remaining six watersheds, the source factor a_s varied from 0.7 $g L^{-1}$ $(mm day^{-1})^{-0.4}$ for Maybar to 1.8 $g L^{-1}$ $(mm day^{-1})^{-0.4}$ for Anjeni. The smaller values are related to watersheds with a minimum of gullying such as Maybar. The greater values are associated with watershed with active gullying 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 between 1.6 $g L^{-1}$ $(mm day^{-1})^{-0.4}$ for the Gilgel Abay and 5.9 $g L^{-1}$ $(mm day^{-1})^{-0.4}$ 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 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 watersheds have 9 % or more in this category. Similarly Anjeni, in which most land is terraced has a low slope and small transport coefficient than the Maybar and Debre Mawi watersheds that do not have terraces and have agricultural land with greater slopes. In both Gilgel Abay (Fig. 3b) and the Anjeni (not shown) watersheds, the concentrations in the beginning of the rainy phase are less pronounced than the other 4 watersheds. Thus, the low value of the transport coefficient is most likely related to the slope of the cultivated land in the watershed.

Finally the "a_b" values that determine the concentration during base flows are related to the stream channel erosion that in the case of the Gumara is the greatest value. This can be related to the human activities in the river for irrigation and sediment taken out from the banks.

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6 Conclusions

In the Ethiopian highlands sediment concentration in the rivers decrease with progression of the rainy phase of the monsoon. Using this observation developing the sediment rating curve significantly improves for predicting the sediment concentration and load. The method developed by the Ministry of Water Irrigation and Electricity and used for predicting daily loads throughout Ethiopia will likely remain the method of choice for most rivers especially for larger basins where concentrations remain relatively constant. Although more research has to be done, there is an indication that the coefficients in the newly developed concentration rating curve can be related to landscape characteristics and therefore might have.

Information about the supplement

The original data of the rating curves are listed in the Supplement.

The Supplement related to this article is available online at doi:10.5194/-15-1419-2015-supplement.

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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 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	0.11	1658	–	–
Maybar	.12	1320	–	–

MoWIE*: Ministry of Water Irrigation and Electricity.

Table 2. 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 $(\mathrm{g\,L^{-1}}\,(\mathrm{mm\,day^{-1}}))^{-0.4}$			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

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Table 3. Performance of sediment concentration predicted by MoWIE (Ministry of Water Irrigation and Electricity) developed load rating curve and the concentration rating curve.

	MoWIE load rating curve		Concentration rating curve	
River/ watershed/	NS	R^2	NS	R^2
Gilgel Abay	0.43	0.46	0.60	0.54
Gumara	−0.022	−0.07	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

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Table 4. Performance measures of sediment load predicted by MoWIE (Ministry of Water Irrigation and Electricity) load rating curve and the concentration rating curve.

	MoWIE load rating curve		Concentration rating curve	
River/ watershed/	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.

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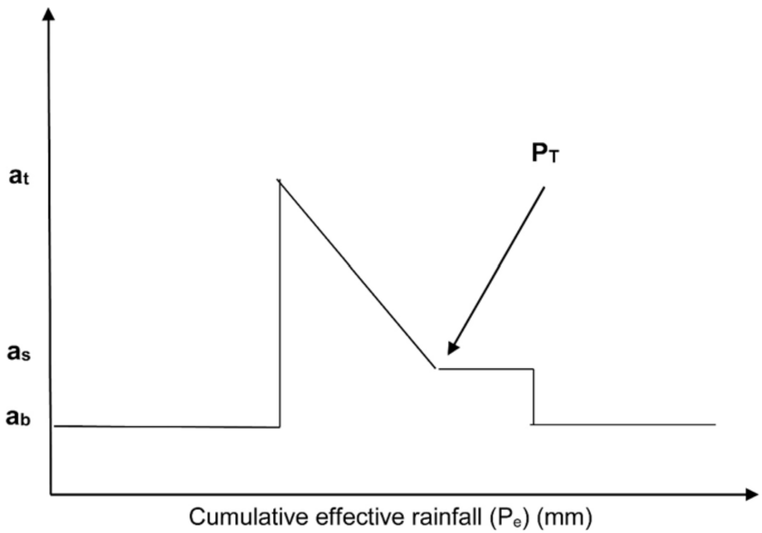

Figure 1. Relationship between sediment concentrations and cumulative effective rainfall.

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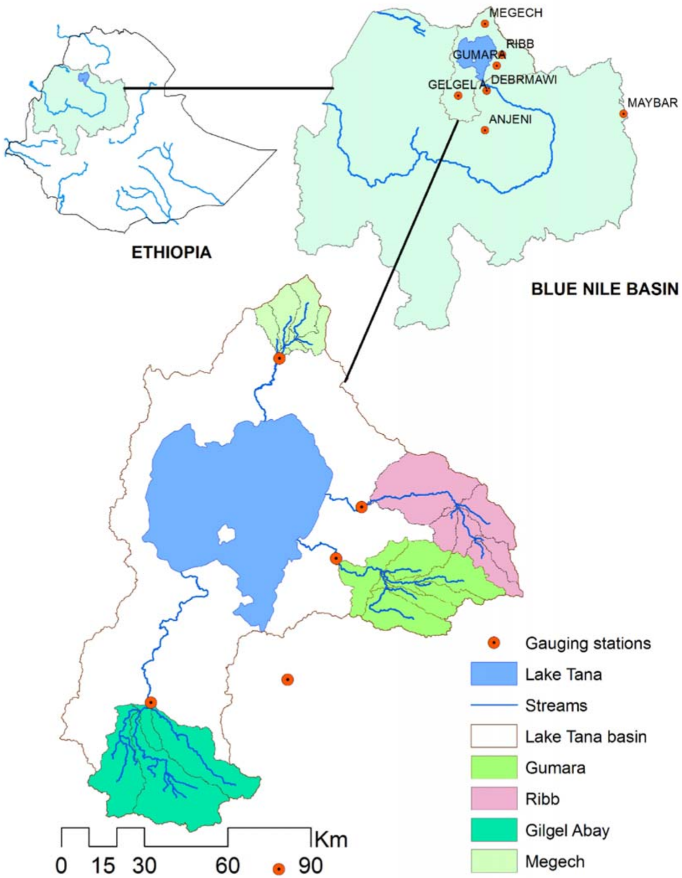

Figure 2. Location map of the four large watershed in the Lake Tana basin, Gilgel Abay, Gumara, Ribb and Megech and 100 ha watersheds in or close to the Blue Nile Basin Debre Mawi, Anjeni and Maybar.

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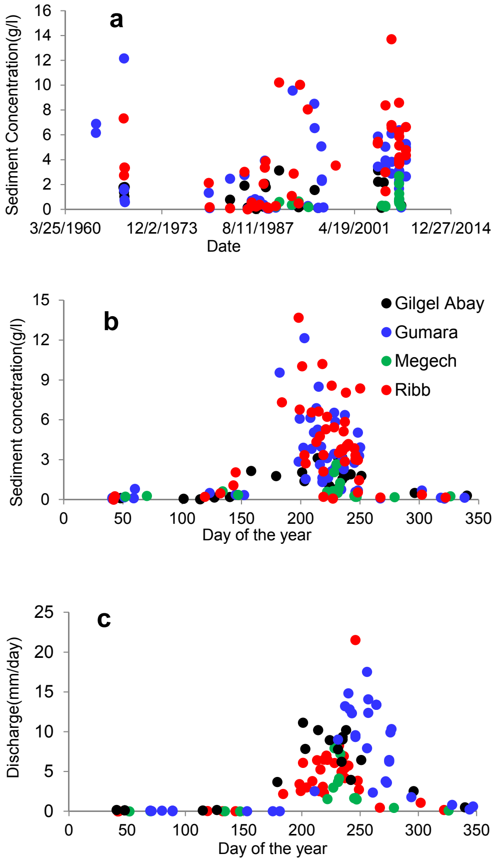

Figure 3. Observed sediment concentration and discharge for the four Lake Tana watersheds: Gilgel Abay, Gumara, Megech and Ribb. **(a)** Sediment concentration vs. date of sampling; **(b)** sediment concentration as a function of day of sampling independent of the year **(c)** observed discharge plotted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

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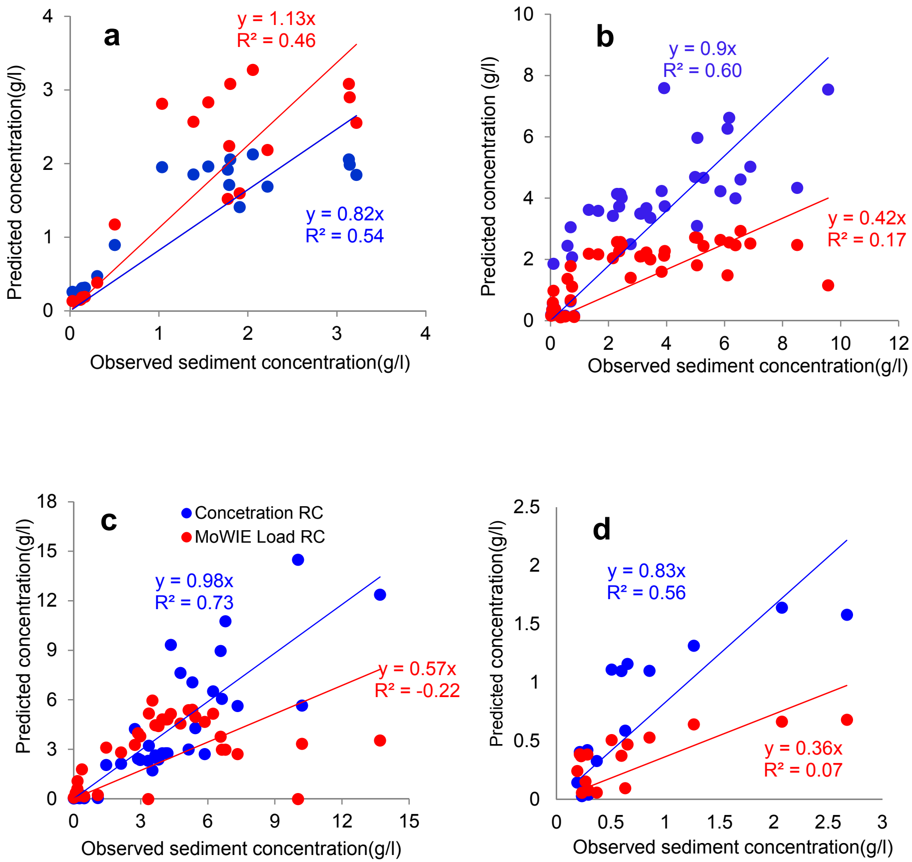

Figure 4. Predicted versus observed sediment concentration using concentration rating curve and MoWIE load rating curve for the watersheds in Lake Tana Basin. **(a)** Gilgel Abay, **(b)** Gumara, **(c)** Ribb, **(d)** Megech.

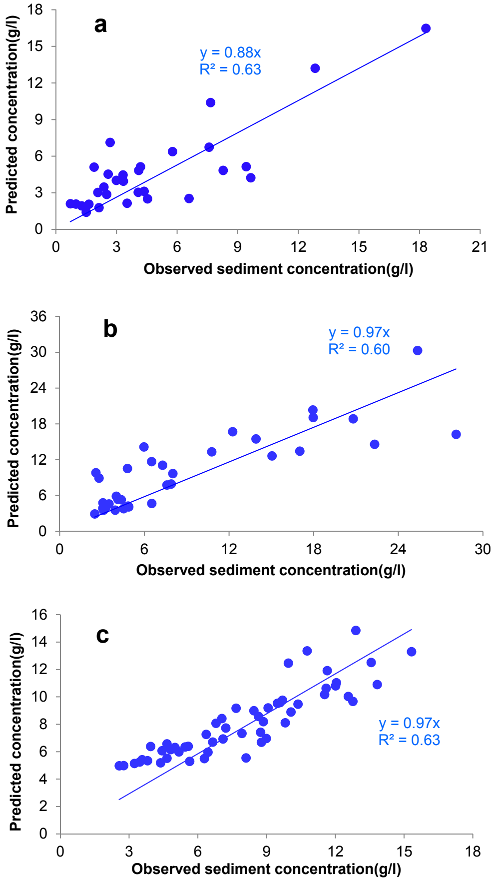

Figure 5. Predicted and observed sediment concentration using concentration rating curve for the 100 ha watersheds **(a)** Maybar, **(b)** Debre Mawi and **(c)** Anjeni.

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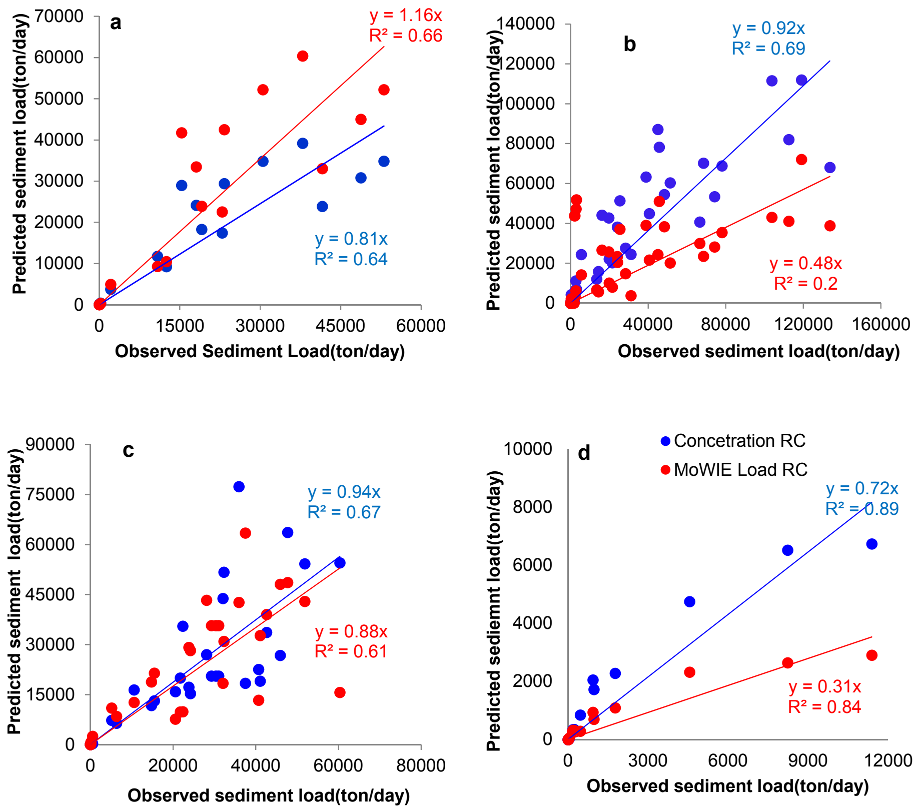

Figure 6. Predicted versus observed sediment load using concentration rating curve and MoWIE load rating curve for the macro watersheds in Lake Tana Basin **(a)** Gilgel Abay, **(b)** Gumara, **(c)** Ribb, **(d)** Megech.