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# Estimating the Sediment Flux and Budget for a Data Limited Rift Valley Lake in Ethiopia

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Received: 15 October 2018; Accepted: 9 December 2018; Published: 23 December 2018

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**Abstract:** Information on sediment concentration in rivers is important for the design and management of reservoirs. In this paper, river sediment flux and siltation rate of a rift valley lake basin (Lake Ziway, Ethiopia) was modeled using suspended sediment concentration (SSC) samples from four rivers and lake outlet stations. Both linear and non-linear least squares log–log regression methods were used to develop the model. The best-fit model was tested and evaluated qualitatively by time-series plots, quantitatively by using watershed model evaluation statistics, and validated by calculating the prediction error. Sediment yield (SY) of ungauged rivers were assessed by developing and using a model that includes catchment area, slope, and rainfall, whereas bedload was estimated. As a result, the gross annual SY transported into the lake was 2.081 Mton/year. Annually, 0.178 Mton/year of sediment is deposited in floodplains with a sediment trapping rate of 20.6%, and 41,340 ton/year of sediment leaves the lake through the Bulbula River. The annual sediment deposition in the lake is 2.039 Mton/year with a mean sediment trapping efficiency of 98%. Based on the established sediment budget with average rainfall, the lake will lose its volume by 0.106% annually and the lifetime of Lake Ziway will be 947 years. The results show that the approach used can be replicated at other similar ungauged watersheds. As one of the most important sources of water for irrigation in the country, the results can be used for planning and implementing a lake basin management program targeting upstream soil erosion control.

**Keywords:** sediment fluxes; rating curve; lake sedimentation; floodplain deposition; sediment budget; Lake Ziway

## 1. Introduction

Sedimentation caused by catchment erosion is reducing a significant proportion of the original storage capacity of many lakes [1]. It is estimated that 1% to 2% of the existing storage volume of reservoirs in the world is lost each year due to sedimentation. For many lowlands, rivers transport sediment from the catchment to lakes [2] and the benefits, lifespan, and the sustainability of lakes can be controlled by sedimentation [3]. Hence, sediment budgeting for lakes is useful to identify the dominant catchment processes and estimate the rate of deposition [4], and it comprises identification and quantification of the sources, pathways, and sinks of eroded material within a catchment [5]. Conceptually [6], a sediment budget consists of three major components: sediment inflow (i.e., eroded soil or sediment yield (SY) transport into depositional area), outflow (i.e., sediment load exported from a depositional area), and the change in storage.

In order to meaningfully manage sedimentation in rivers and reservoirs, there is a need to understand, define, quantify, and/or predict catchment soil erosion and sediment yield [7]. For a river basin, the sediment yield can be obtained by calculating from sediment data at gauging stations [8]; analyzing reservoir sedimentation data [9]; estimating using sediment transport equations [6], and/or predicting using models [10–24]. While, different erosion and sediment yield prediction methods are in use, no single catchment erosion and sediment yield prediction method can be presumed to be applicable to all possible conditions [25,26]. All methods have limitations and advantages, and the choice of method to apply should consider a number of influencing factors. These factors include catchment characteristics, site conditions, ecological considerations, dam engineering requirements, availability of time, economics, data requirements, and data availability.

For instance, to obtain the indicator for environmental changes like lake sedimentation, lake ecosystem functioning, and to estimate the life time of reservoirs [27–29], the bathymetric surveying method is the most accurate. But, in quantifying both soil erosion and deposition rates, the sediment budgets estimated from repeated bathymetric surveys cannot indicate the actual soil loss rate of the catchment. In the same way, for river basin and reservoir management, using an empirical model is one of the popular means of estimating sediment loads. In predicting soil loss, the most commonly used empirical models are the universal soil loss equation (USLE) [30] and its derivatives. However, in the case of developing countries like Ethiopia, it is cumbersome to obtain the required data for these models [31]. The reason is that these models were originally developed for areas that have large amounts of data; and 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. Next to modeling, direct sampling of sediment in rivers and using sediment transport equations are among the popular means of estimating sediment loads and their respective transport. While direct measurement is the most preferred and trusted method, it is not always practical; it is expensive and laborious. For most rivers, observed data are limited and fragmented. To generate sediment load for areas of limited continuous observation, the use of rating curves is recommended [2]. Today, a rating curve is commonly used by engineers and scientists for various purposes [22]. Sediment rating curves are especially used by engineers and hydrologists to estimate the life expectancy of dams, while scientists use it to study depositional and erosional environments [32]. For example, a rating curve has been applied to the Yangtze River, China, for trend analyses [33]; for sediment rating curve modification of the Marun Dam, Iran [34]; for sediment load estimation in Algeria in the Mellegue River Basin [35], to estimate the Rhône River contribution for Lake Geneva [36]; to assess the sediment concentration rating for the upper Blue Nile [37]; and to revise lake sediment budgets of Lake Tana, Ethiopia [38].

In addition, there is a connection between semi-distributed 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 [39–41], and in the Lake Ziway basin [42], used sediment load rating curves to generate the observed sediment load data for calibrating and validating the sediment load in the Soil and Water Assessment Tool (SWAT). Studies indicate that the predicted suspended sediment load from sediment rating curve techniques is either underestimating [2,43] or overestimating [44] the sediment load when compared with the corresponding observed sediment load. To compensate for this, some modifications have been applied; these include applying correction factors [45] and using non-linear regression methods [43]. Even though there are different compensation methods employed to develop a sediment rating curve, none of them have received universal acceptance [8]. The predicting quality of a given sediment rating curve will depend on the fitting methods, and a single sediment rating curve cannot be employed for all rivers. Hence, developing a best-fit model is required in order to be accurate in sediment estimation. Reference [46] suggests to develop a best-fit rating curve model to estimate long-term suspended sediment data records for rivers with a limited sediment database.

The Lake Ziway basin is one of the data scarce areas of Ethiopia and the historical measured sediment data is very limited. Hence, studying the sediment budget of the basin is necessary to obtain more realistic information regarding the rate of siltation and the implications of the annual loss of lake storage over time. Moreover, according to Reference [47] there are two proposed dam sites on its tributary rivers for multipurpose use. This necessitates studying sediment accumulation rates and evaluating best management options to increase the life span of the lake by reducing upland soil erosion and lake sedimentation. Hence, the objectives of this study are to (1) develop the best-fit rating curves to estimate suspended sediment loads; (2) estimate overbank sedimentation on the floodplains of the Lake Ziway tributary rivers; and (3) establish a sediment budget of the lake.

## 2. Study Area

### *2.1. Location and Topography*

Lake Ziway is located in the Central Ethiopian Rift Valley basin (Figure 1), where it fills a depression at an elevation of about 1637 m above sea level. The lake is the shallowest lake in the country and drains to Lake Abiyata. It is the third largest freshwater lake of the Ethiopian Rift Valley lakes and the fourth in the country. The lake has a surface area of 423 km$^2$ and has five islands: namely Gelila, Debre Sina, Tulu Gudo, Tsedecha, and Fundro. The lake basin has a total area of 7285 km$^2$ and geographically it extends from 7°20′54″ to 8°25′56″ latitude and 38°13′02″ to 39°24′01″ longitude. The majority of the watershed is flat to gently undulating, but is bounded by a steep slope in the eastern and southeastern escarpments and is characterized by abrupt faults. There is a topographic difference of about 2600 m between the rift floor and the highland areas (mountains) of the basin.

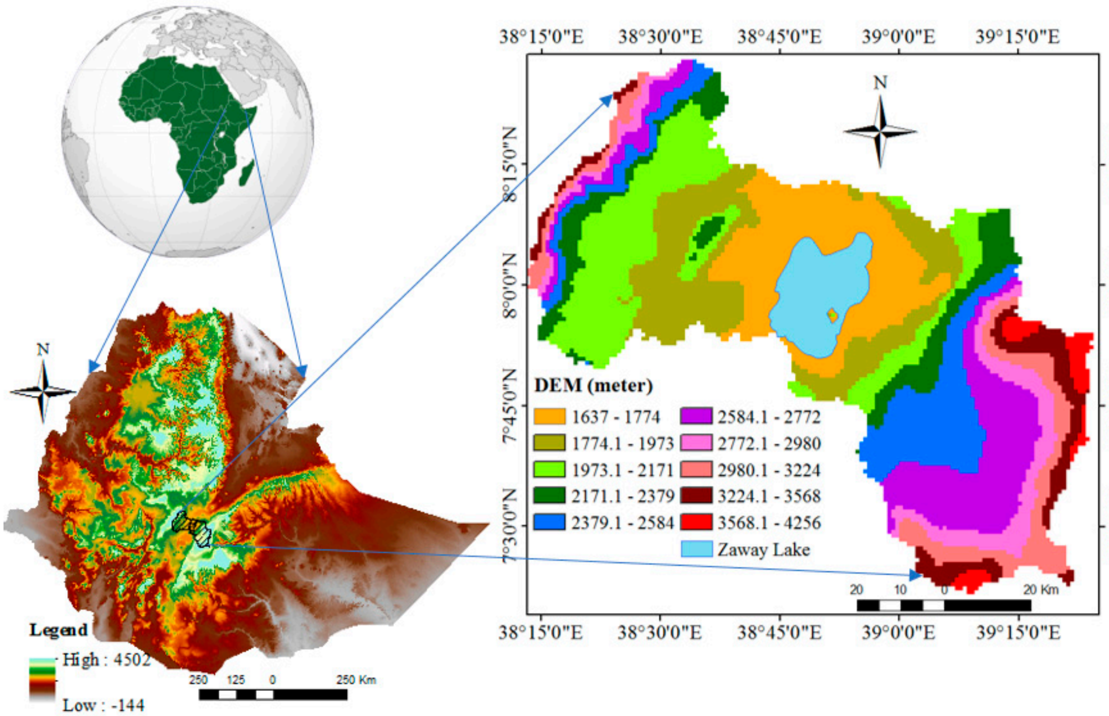


**Figure 1.** Location of the Lake Ziway basin in the Ethiopian Rift Valley.

### *2.2. Climate*

The climate of the Lake Ziway basin is dry to sub-humid or humid. The lowland area surrounding the lake is arid or semi-arid, and the highlands are sub-dry humid to humid. The basin is classified into three main seasons based on its rainfall [48]. The long rainy season is summer and is locally known as Kiremt. The Kiremt rain represents 50–70% of the mean annual total rainfall. The dry period extends between October–February, locally known as Bega. The small rainy season, known as Belg, represents 20–30% of the annual rainfall and occurs from March–May.

The long-term (1987–2016) mean annual rainfall of Arata, Bekoji SF, Ketera Genet, Kulumsa, Meraro, Ogolcho, Adamitulu, Bui, Butajra, Koshe, Maki, and Ziway meteorological stations ranges from 620 to 1225 mm, and the areal map of rainfall depth by using the inverse distance square interpolation method (IDW) is shown in Figure 2.

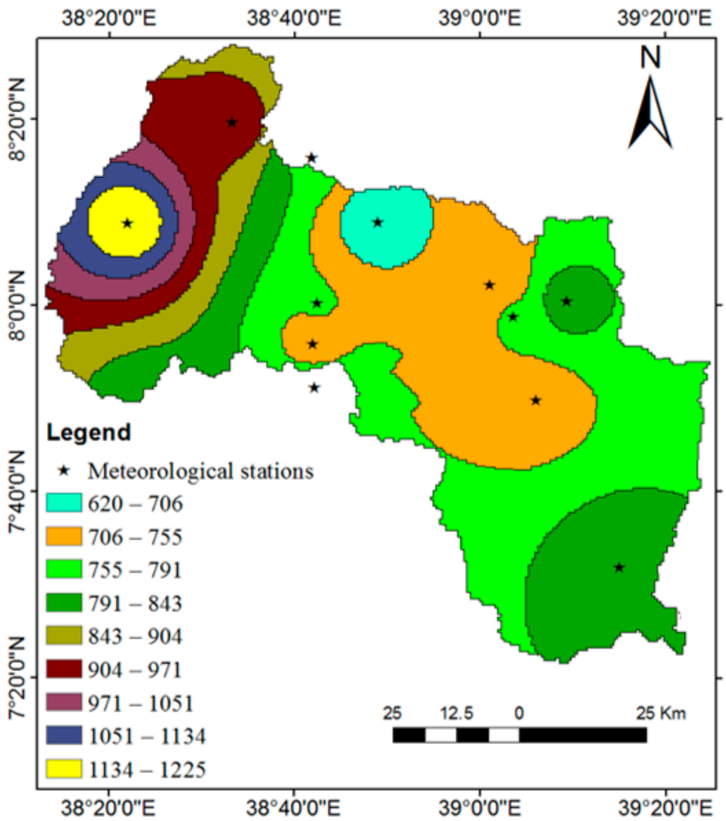


**Figure 2.** Average annual rainfall depth (1989–2016) in the Lake Ziway basin based on the inverse distance square interpolation method (IDW) of data using nearby meteorological rain gauge stations.

## *2.3. Hydrology*

The lake is fed by two main rivers, the Katar and Maki rivers, and overflow into the Bulbula River. The Katar River is the biggest perennial river and has a total watershed area of 3350 km$^2$. Maki River drains an area of 2433 km$^2$ from the west and northwest of Lake Ziway. Analysis of the streamflow data indicated that as the Katar is feeding the lake with an average annual runoff volume of 401.6 Mm$^3$, it attains a maximum discharge of 110 m$^3$/s in the month of August and a minimum discharge of 1.6 m$^3$/s in the month of January. Similarly, Maki River is feeding Lake Ziway with average annual runoff volume of 270.24 Mm$^3$ and it attains its maximum discharge of 95 m$^3$/s in the month of August. During November to January, the river bed is dry and the base flow of the river is almost nil during the severe dry seasons of the year. Regarding its outflow, Lake Ziway discharges into the Bulbula River with a mean annual runoff volume of 116.3 Mm$^3$.

## *2.4. Geology, Soil, and Land Use*

The geology of the basin is mainly dominated by basalt. This basaltic group is comprised of Wonji and Silte volcanics. The Wonji lava field is located at the eastern escarpment of Lake Ziway, and the other lava field, Silte, is located at the western escarpment [49]. Next to basalt, alluvial deposits are also scattered around the lake. The soil of the Lake Ziway basin is closely related to parental material and degree of weathering [50]. The six most dominant soil types are andosols, cambisols, fluvisols leptosols, luvisols, and vertisol [47].

Regarding land use types, in the basin, agriculture has a long history. The basin as a whole is a zone of intensive agricultural activities and there is dynamic land-use changes [47]. In the year 2010, the sediment delivery rate of the western sub-basin of the lake was assessed, and from the total basin around 14% was highly eroded with an average sediment yield (SY) of 50–106 ton/ha/year, 24% had an average SY of 20–50 ton/ha/year, and the remaining 62% was slight to moderately eroded with an average SY rate of 0–20 ton/ha/year [47]. When we did a field visit and assessment for the case of Katar (eastern lake sub-basin), we observed a seriously eroded area inside the sub-catchments.

## 3. Methodology

Sedimentation is of particular importance to reservoir managers, who must plan for the eventual and inevitable loss of reservoir storage. Reservoir sedimentation is the end effect of catchment erosion and the eroded soil is then transported along with any surface runoff, mainly due to precipitation, and becomes a part of the sediment load in the tributary rivers. In this study, to determine the net sediment deposition rates of Lake Ziway, both historical and newly measured sediment flow rates of its tributary rivers were used. The detailed workflow diagram of the study procedure is shown in Figure 3.

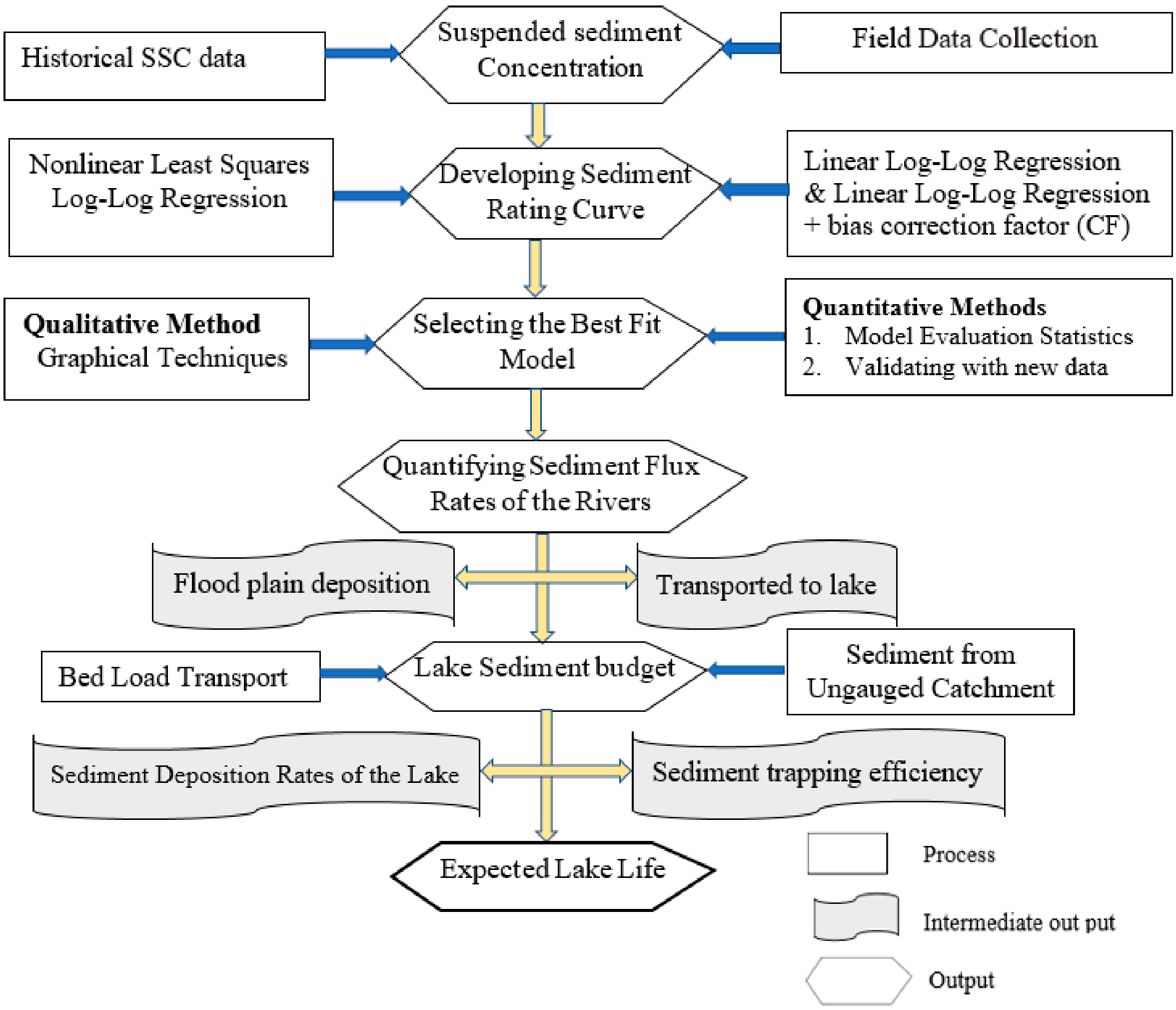


**Figure 3.** The workflow diagram used for the study.

### *3.1. Historical Data Collection*

Regularly measured discharge and irregularly measured sediment concentration data were acquired from the Ethiopian Ministry of Water Irrigation and Electricity (MoWIE) for the two major rivers (Figure 4) in the Lake Ziway basin for the period of 1989 to 2013. Additional suspended sediment samples were collected from four river gauging stations and one lake outlet from mid-2016 to mid-2018 to validate the developed model.

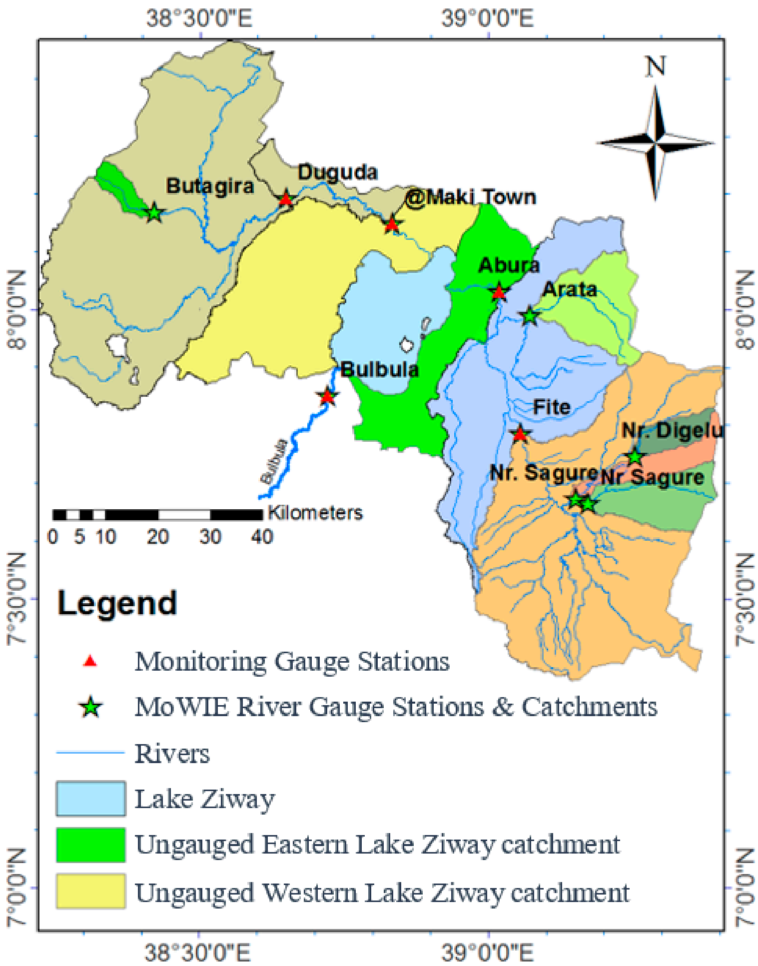


**Figure 4.** Ziway Lake basin river monitoring gauge stations collected from the Ethiopian Ministry of Water Irrigation and Electricity (MoWIE).

### *3.2. Field Data Collection*

From each monitoring station, the suspended sediment concentrations (SSCs) of the rivers were sampled in both wet and dry seasons. For the collection of suspended sediment (SS) samples, the total stream width was divided into four equal widths, and individual depth-integrated samples were collected at the centroid of each increment. As the stream flow gauges are near the bridges, during high-flow season, the suspended sediment samples were collected by standing on a bridge using depth-integrated suspended-sediment samplers according to procedures outlined in Reference [51]. Individual samples from each centroid were kept primarily in one-pint glass bottles, with each vertical increment generally contained within a single bottle. Care was taken not to overfill the sample bottle. If a bottle was inadvertently overfilled, the contents were discarded, and the vertical increment was re-sampled.

The sampled water taken from each station was kept in the 600 mL bottles and the gravimetric method was used to analyze the SSCs in mg/L. Gravimetric methods involve filtering the sediment from a known sample volume using a vacuum filtration process [52]. During the high-flow season, the concentration of sediment was high, and in such cases, a pre-weighed dish was used to evaporate a measured portion of the sample to determine the weight of the residue according to procedures outlined in Reference [53].

The river cross-sectional profile was assessed in low- and medium-flow seasons using a few hydrological apparatuses, and the flow velocity of the rivers were tested by current meter. For all monitoring stations, there was a staff gauge equipped by MoWIE and used to convert the river stages into flow discharge.

### *3.3. Estimating the Suspended Sediment Yield through Regression Relationship*

Because of the scarcity of continuous sediment data, estimates are often derived from empirical relations between river discharges and corresponding suspended sediment concentrations/loads which is called as rating curve [54] and is equated as

$$\text{Log}\ (Qs) = a + b * \text{Log}\ (Q_w) \quad (1)$$

where $Qs$ is suspended sediment transport (ton/day), $Q_w$ is daily stream flow ($m^3/s$), and $a$ and $b$ are regression coefficient and exponent, respectively.

Sediment load calculated using the above relation has been reported as it is underestimating the actual suspended sediment loads [45]. A bias correction factor (CF) was introduced and the SSC rating curve was corrected as:

$$\text{Log}\ (Qs) = a + b * \text{Log}\ (Q_w) + \text{CF} \quad (2)$$

Reference [45] proposed a statistical bias correction factor (CF) equal to $\exp(2.65S^2)$ to reduce the degree of underestimation by rating curve with

$$S^2 = \frac{\sum_{i=1}^{n} \left(\text{Log}\ (Ci) - \text{Log}\ \left(\hat{C}i\right)\right)^2}{n-2} \quad (3)$$

where $S^2$ is the variance, $Ci$ and $\hat{C}i$ are observed and predicted values, and $n$ is the number of observations.

In this study, the normal linear log–log regression, the normal log–log regression with correction bias factor, and the non-linear least squares regression methods were used to derive the sediment yield from measured suspended solids data. Non-linear with optimization procedure is derived as:

$$\text{Log}\ (Qs) = a + b * (\text{Log}\ Q_w)^c \quad (4)$$

where $a$, $b$, and $c$ are coefficients determined through a regression and optimization procedure using the Microsoft Excel Solver Tool by setting an objective function to minimum as indicated in Reference [2].

By using those three methods (Equations (1), (2), and (4)), sediment rating curves were developed for all monitoring stations and the most appropriate sediment rating curve was selected based on goodness-of-fit. The goodness-of-fit of the rating curves were evaluated and tested statistically by using five widely used statistics namely: coefficient of determination ($R^2$), Nash–Sutcliffe efficiency (NSE), root mean square error (RMSE), observations standard deviation ratio (RSR), and percent bias (PBIAS). Their recommended value to test the performance of the models is shown in Table 1 [55].

**Table 1.** General performance ratings for recommended statistics to evaluate models [55].

| Statistics | Performance Rating | | | | |
|---|---|---|---|---|---|
| | Excellent | Very Good | Good | Fair | Unsatisfactory |
| $R^2 = \frac{\left(\sum_{i=1}^{n}(SSC_i^{obs} - SSC_{obs}^{mean})(SSC_i^{Sim} - SSC_{Sim}^{mean})\right)^2}{\sum_{i=1}^{n}(SSC_i^{obs} - SSC_{obs}^{mean})^2 \sum_{i=1}^{n}(SSC_i^{Sim} - SSC_{Sim}^{mean})^2}$ | (0.9–1) | (0.75–0.9) | (0.65–0.75) | (0.5–0.65) | (0–0.5) |
| $NSE = 1 - \frac{\sum_{i=1}^{n}(SSC_i^{Sim} - SSC_{Sim}^{mean})^2}{\sum_{i=1}^{n}(SSC_i^{obs} - SSC_{obs}^{mean})^2}$ | (0.9–1) | (0.75–0.9) | 0.65–0.75) | (0.5–0.65) | (−∞–0.5) |
| $RMSE = \sqrt{\sum_{i}^{N}(SSC_i^{obs} - SSC_i^{sim})^2 / \frac{1}{N}}$ | (0–0.25) | (0.25–0.5) | (0.5–0.6) | (0.6–0.7) | (0.7–+∞) |
| $RSR = \frac{\sqrt{\sum_{i=1}^{n}(SSC_i^{obs} - SSC_i^{Sim})^2}}{\sqrt{\sum_{i=1}^{n}(SSC_i^{obs} - SSC_{obs}^{mean})^2}}$ | (0–0.25) | (0.25–0.5) | (0.5–0.6) | (0.6–0.7) | (0.7–+∞) |
| $PBIAS = \frac{\sum_{i=1}^{n}(SSC_i^{obs} - SSC_i^{Sim}) * 100}{\sum_{i=1}^{n}(SSC_i^{obs})}$ | (0–±5) | (±5–±15) | (±15–±30) | (±30–±55) | (±55–±∞) |

SSC, daily measured suspended sediment load (ton/day); *N*, number of samples; $R^2$, coefficient of determination; NSE, Nash–Sutcliffe efficiency; RMSE, root mean square error; RSR, observations standard deviation ratio; PBIAS, percent bias.

Furthermore, to validate the methods, the relative errors of estimation were calculated from measured suspended sediment concentrations and the predicted suspended loads as:

$$\text{Error}\ (\%) = \frac{(\text{Rating Curve Estimate} - \text{Measured value})}{\text{Measured value}} \times 100\% \quad (5)$$

The predicted and measured sediment loads were computed by plotting the graph between observed and computed data.

### *3.4. Suspended Sediment Load Deposited on Floodplains*

Due to periodic flooding and sediment deposition, large areas of floodplain in the eastern and western parts of the Lake Ziway basin were formed on top of the exhumed lake deposits [56]. Overbank sedimentation on floodplains can result in a significant abstraction of the suspended sediment load transported by a river, and thus, represents an important component of the catchment sediment budget [57]. As shown in Figure 5 below, there is the phenomenon of floodplains along the rivers and sand mining activities across sections of the rivers. Hence, the soil lost on the floodplains needs to be quantified. However, no study has been done in the Lake Ziway basin to estimate the amount of sediment deposited on its floodplains.

**Figure 5.** Floodplain area of the lower Maki River.

To quantify the deposition rate on floodplains and river channels, suspended sediment and discharge measurements were taken at the upper and lower monitoring stations of the Maki and Katar rivers (i.e., Duguda and Maki town stations for Maki River and Fite and Abura for Katar River, Figure 4), which cross large floodplains in the low-lying catchment areas and have a length of 41.6 and 37.5 km inside of Maki and Katar, respectively. Deduction of the sediment yield at the lower gauge station from that at the upper station results in the sediment load (Load A) deposited on parts of the floodplains and river channels that lay between the two stations. To estimate the sediment deposited in the parts of floodplains and river channels that are located in between the lower monitoring station and the lake (Load B), the deposition rate per unit river length is assumed constant along the river reach. Then, the values of Load B were estimated as:

$$\text{Load B} = \frac{\text{LL 1}}{\text{LL2}} \times \text{load A} \quad (6)$$

where LL1 is the length (Km) of the river reach between the two gauges and LL2 is the length (Km) of the river reach between the lower station and the lake.

Finally, Load A and Load B were summed to produce the net sediment mass deposited on floodplains that border the river.

### 3.5. Application of the Regression Relationships to Ungauged Watersheds

Around 22% of the basin with notable flat areas did not have observed suspended sediment data (Figure 4). Hence, the annual suspended sediment yield from ungauged catchment was estimated by establishing an empirical regression model that relates sediment yield of the gauged stations to several catchment characteristics, namely drainage area, slope, and average annual rainfall amount. The three explanatory factors were calculated for gauged and ungauged river catchments, i.e., areas of catchments and slope were processed from the digital elevation model (DEM) and their mean annual area rainfall was calculated based on the inverse distance weighted interpolation of the nearby meteorological stations (Figure 2).

### 3.6. Suspended Sediment Outflow from Lake Ziway

The limited measured suspended sediment concentrations at the Bulbula River gauging station were obtained from MoWIE and during field data collection, and SSCs of the outflow river were sampled in both wet and dry seasons. To estimate the annual suspended sediment mass leaving the lake, a rating curve was developed from data collected from the field and historically existing data.

### 3.7. Estimation of Bed Load

The total sediment load of streams usually is considered to be the sum of two components, called suspended load and bedload. However, in most studies in Ethiopia, the bedload component is frequently ignored due to measurement constraints [58–60]. In most rivers, bed load to suspended load ratio is in the range of 10% to 30% [61], and in mountain rivers (high slope) ranges up to 35% of the suspended load [62]. In this study, the Maki and Katar rivers flow on gentle slopes for more than thirteen kilometers before joining Lake Ziway. Hence, we assumed the bedload was 10% of suspended sediment load.

### 3.8. Sediment Budget of Lake Ziway

The sediment budget in its simplest form [63] for a lake is:

$$SY_{in} = SY_{out} + \Delta S \tag{7}$$

For establishing the sediment budget of Lake Ziway, Equation (7) was refined and reorganized as:

$$\Delta S_{LZ} = SY_g + SY_u + SY_b - SY_{bl} \tag{8}$$

where $\Delta S_{LZ}$ is the net annual sediment deposition in Lake Ziway, SYg and SYu are the annual suspended sediment yields transported into the lake from gauged and ungauged rivers, respectively, SYb is the annual bedload transported into the lake, and $SY_{bl}$ annual sediment yield exported from the lake through the Bulbula River.

### 3.9. Sediment Volume and Lake SedimentTrapping Efficiency

To obtain the rate of sedimentation in the lake, an average specific weight of lake sediment is required. Sediment core samples were collected from ten points from the shore of the lake and undisturbed samples were dried for 24 h at 105 °C and the mean bulk density (BD) of 1.22 ton/$m^3$ was determined.

The sediment trapping efficiency (Tef) of the lake was calculated as

$$\text{Tef}(\%) = \frac{(\text{SYin} - \text{SYout})}{\text{SYin}} \times 100 \tag{9}$$

where $SY_{in}$ and $SY_{out}$ are inflowing and outflowing sediment load (in ton/year).

## 4. Result and Discussion

### *4.1. Suspended Sediment Discharge from Gauged Catchments*

Both historical and newly measured suspended sediment data were used to estimate the suspended sediment loads of the rivers. The average suspended sediment concentration of all samples was 1.9 (±1.8) g/L and the average estimated sediment yield was 3.5 (±4.8) × $10^3$ ton/day. During strong floods in the rainy season, its suspended sediment concentration could reach up to 8600 mg/L and SY could reach up to 31.9 × $10^3$ ton/day. Despite the limited range of suspended sediment yields in the dry season and the rather large scatter in a few cases, a clear trend in mean sediment yield was observed at most of the monitoring stations, i.e., for a given river discharge, suspended sediment concentration values were smaller towards the end of the rainy season (September) than at the beginning of the Belg—small rainy season. This may be related to the depletion of sediments and the development of a vegetation cover through the rainy season. Despite the fact that no study has been done on the sediment mechanics of the Lake Ziway tributary rivers, a similar pattern was found by a study done in Northern Ethiopia in Reference [38] on tributaries of Lake Tana and by Reference [64] in the Geba catchment of Northern Ethiopia.

#### 4.1.1. Sediment Rating Curve Development

To estimate the siltation rate of Lake Ziway and the sediment contribution rates of its sub-catchments, rating curves with normal linear log–log regression (Equation (1)), normal linear log–log regression with correction factor (Equation (2)), and non-linear least squares regression (Equation (4)) methods were established for all monitoring gauging stations (Figure 6).

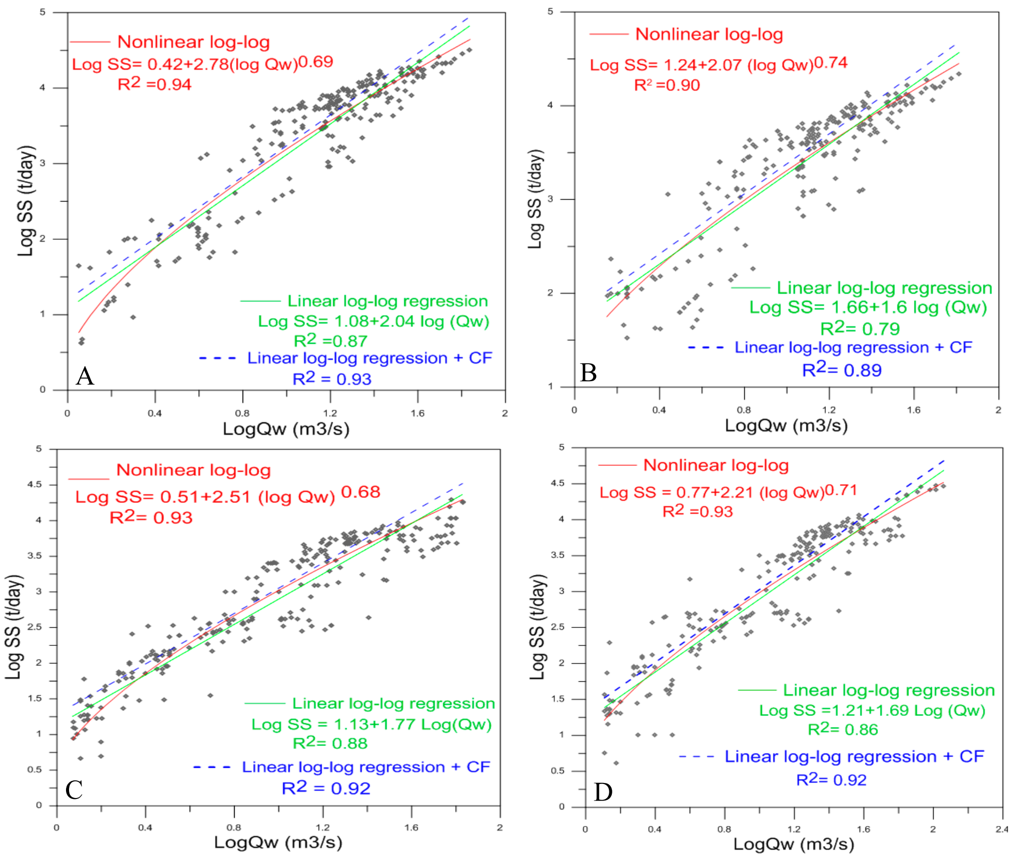


**Figure 6.** The developed rating curves (**A**) at station Duguda; (**B**) Maki; (**C**) Abura; and (**D**) Fite.

The comparison plots between measured and computed data with three different rating curves, namely rating curve developed by normal linear log–log regression (Equation (1)), normal linear log–log regression with correction factor (Equation (2)), and non-linear least squares regression (Equation (4)) is shown in figure (Figure 7).

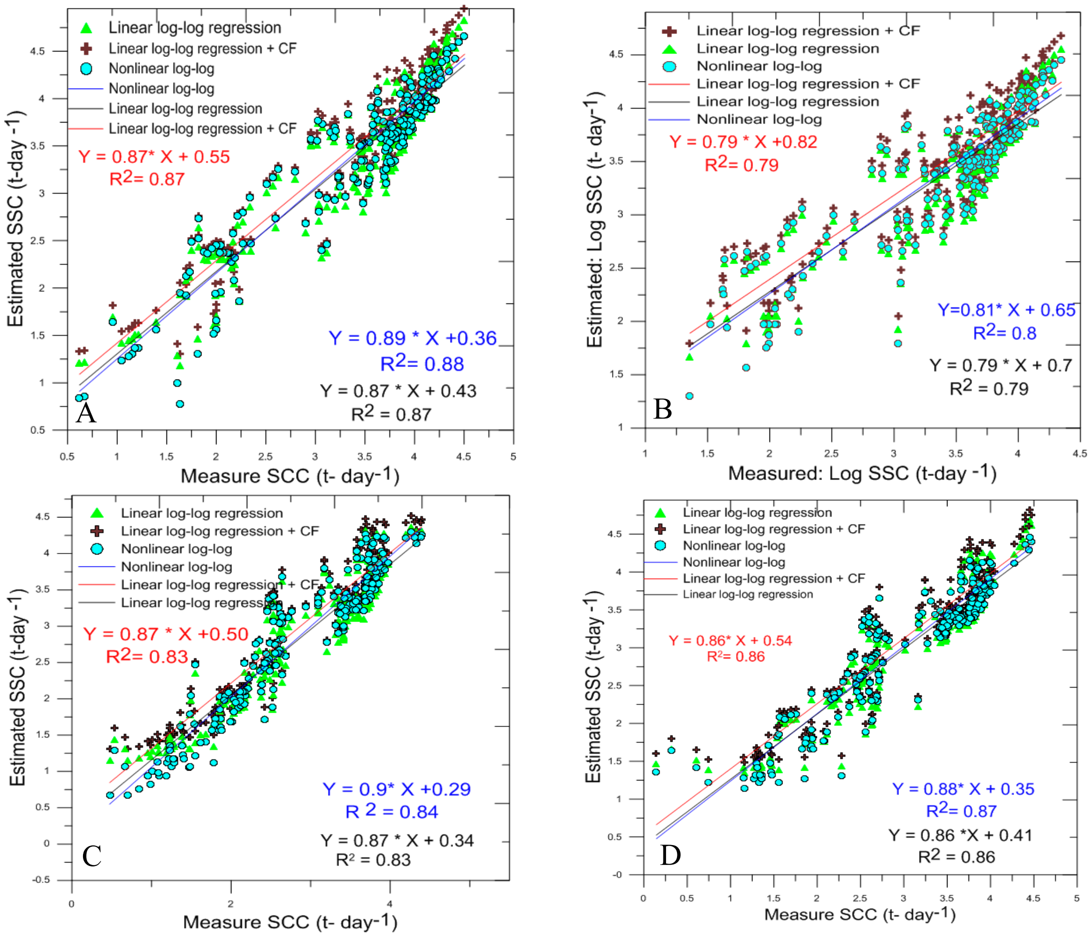


**Figure 7.** Predicted and observed SSCs at station (**A**) Duguda; (**B**) Maki; (**C**) Abura; and (**D**) Fite.

Similarly, for the lake outlet station (Bulbula River), the sediment rating curve was developed as shown in Figure 8A by using Equations (1), (2), and (4), and the comparison plot between measured and computed data is shown in Figure 8B.

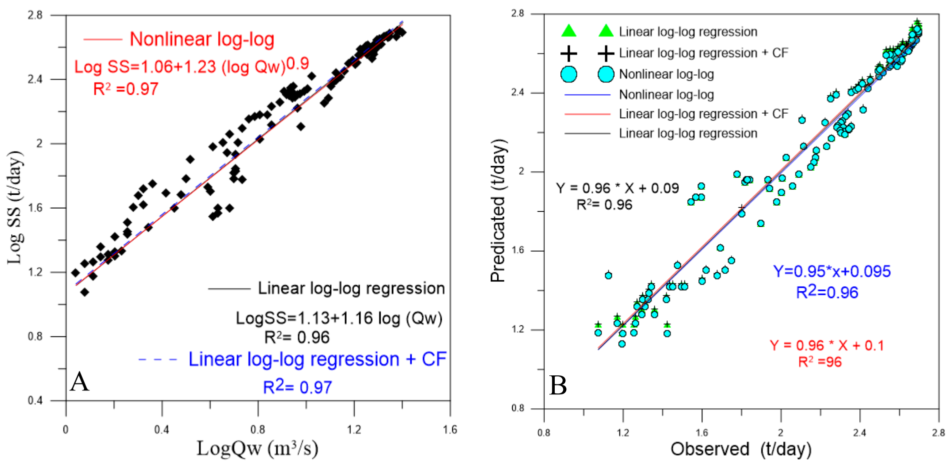


**Figure 8.** (**A**) The developed rating curves for station Bulbula; and (**B**) Predicted and observed SSCs.

As shown in Figure 6, for all monitoring river stations, the model developed by the non-linear least squares regression method was below from both low- and high-stream flows. For medium stream flow, it was between the model developed by linear log–log regression and its corrected one. Hence, this may represent the real condition of the study basin. In the basin, the sediment concentration of the rivers did not increase proportionally with discharge (rainy phase). This can be explained by various reasons. At the beginning of the rainy season, in most parts of the basin, newly plowed land for agriculture facilitates the removal and transportation of soil by runoff. At the end of the rainy season (during river Peak low), the concentration of sediment is low due to plant cover protection of lands. Lastly, during most dry seasons, the tributary rivers carry less sediment until the rainy phase starts. In addition to this, the calculated correlation coefficient ($r^2$) between observed and computed sediment for the model developed by linear log–log regression was also low. Hence, the time series plots graph developed in Figure 6 indicates the use of non-linear least squares regression method as a better alternative to the sediment rating curve in the prediction of sediment load.

In the literature, there are two controversial ideas concerning sediment rating curves and sediment prediction. Some state that rating curves developed based on linear log-transformed data underestimate and others present it as overestimating when compared with the corresponding observed sediment loads. To compensate its degree of underestimation, the bias correction factor was also developed. Others have stated that there is no best method to develop sediment rating curves. To validate these controversies, let us take any of the developed rating curves from Figure 6. As shown in Figure 6, the model developed by the linear method underestimates observed sediment loads for medium-flow seasons. Hence, those who propose to use the bias correction factor are applicable for this section only. In our basin, this position is the time where the rainy phase starts, and more sediment concentrations were observed. Next to that there is a point in which both curves are crossed with each other. This is the point in which both methods are predicting equal sediment loads. Therefore, the authors decided to use any type of ratings curve in these sections only. Lastly, for minimum-flow and peak-flows seasons, there are over predictions. Due to this, we suggested that unless sediment rating curves are developed for each season of the year using linear log–log regression methods, there will be a limitation in compensating for all of the seasons of the year.

The performance of the developed sediment rating curves was evaluated using model evaluation statistics and the results of goodness-of-fit test statistics were determined as follows (Table 2).

**Table 2.** Developed rating curves for river monitoring stations.

| Rating Curve | | Stations | | | | |
|---|---|---|---|---|---|---|
| | | **Maki** | **Duguda** | **Abura** | **Fite** | **Bulbula** |
| Linear log-log Regression<br>Log (SS) = $a + b * \log (Q_w)$ | $R^2$ | 0.79 | 0.87 | 0.88 | 0.86 | 0.96 |
| | NSE | 0.79 | 0.87 | 0.85 | 0.86 | 0.96 |
| | RSR | 0.46 | 0.36 | 0.38 | 0.37 | 0.21 |
| | PBIAS | 0.23 | 0.15 | 0.74 | 0.29 | −0.03 |
| | RMSE | 0.33 | 0.32 | 0.35 | 0.34 | 0.08 |
| Linear log-log Regression + CF<br>Log (SS) = $a + b * \log (Q_w)$ + CF | CF | 0.1 | 0.12 | 0.15 | 0.13 | 0.01 |
| | $R^2$ | 0.89 | 0.93 | 0.92 | 0.92 | 0.97 |
| | NSE | 0.77 | 0.86 | 0.83 | 0.85 | 0.96 |
| | RSR | 0.48 | 0.38 | 0.41 | 0.39 | 0.21 |
| | PBIAS | −3.33 | −3.42 | −4.23 | −4.06 | −0.49 |
| | RMSE | 0.35 | 0.34 | 0.37 | 0.36 | 0.08 |
| Non-Linear log-log Regression<br>Log (SS) = $a + b * (\log Q_w)^c$ | $R^2$ | 0.90 | 0.94 | 0.93 | 0.93 | 0.97 |
| | NSE | 0.80 | 0.88 | 0.87 | 0.87 | 0.96 |
| | RSR | 0.45 | 0.34 | 0.36 | 0.36 | 0.21 |
| | PBIAS | 0.02 | 0.06 | −0.61 | 0.28 | 0.38 |
| | RMSE | 0.32 | 0.31 | 0.33 | 0.33 | 0.08 |

The outperformed model was selected based on minimum RMSE, RSR, and PBIAS, and maximum NSE and $R^2$. Reference [55] recommended that if the $R^2$ and/or NSE has a value of >0.9, 0.9 to 0.75, 0.65 to 0.75, or >0.50, the model can be rated as excellent, very good, adequate, and satisfactory, respectively, in predicting sediment yield. In this study, therefore, we found the $R^2$ values estimated by non-linear regression method for all stations was under excellent and for linear regression under very good except the Bulbula Station (lake outlet). Based on NSE, RMSE, RSR, and PBIAS, all of the three-model predictive performances were very good. As the data used for the model development were few in number, some statistical results indicate that the three developed models have an ability to estimate equally. But compared with their magnitudes, for all statistical parameters developed, the non-linear method is better than the others, and this has been confirmed in the graphical results shown in Figure 6.

The Bulbula River is an outflow location of the lake and the determined graphical as well as statistical model results are different from the others (Figure 8 and Table 2). As shown in Figure 8, the developed sediment rating curves of the three methods and the observed and estimated sediment by the developed rating curves overlapped with each other. This indicates the model developed by all of the methods were equal in predicting the sediment load. Practically, the results may be logical. As the station is the outflow location of the lake, the sediment concentration will depend on the amount of outflow and not on the seasonal rainfall amount. As the lake has its own sediment retention period, the monthly/daily variation of sediment is due to the lake outflow rate difference but not on seasonal sediment inlet rates (Figure 9). For the case of inlet rivers, similar amounts of discharge will have different amounts of sediment concentration, and hence, a non-linear method may be an appropriate one. But for the case of the lake outlet, a model developed by any method can be used. For example some authors including Reference [8] advise to use any method to develop sediment rating curves.

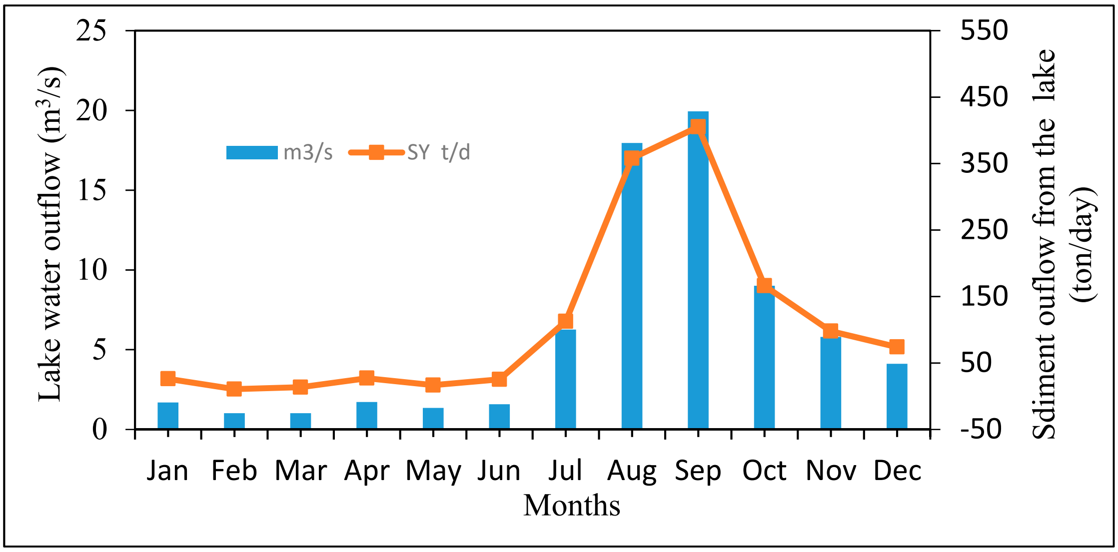


**Figure 9.** Monthly variation of mean suspended sediment concentration (SSC) and lake outlets.

By applying the developed models, the correlation of predicted and observed sediment were tested by slope and $y$-intercept values (Figure 7). In the model evaluation, the existence of low slope indicates the better performance. Hence, for all stream monitoring stations, the predicted performance of rating curves developed by the non-linear least squares regression method were better and the results were similar with other statistics obtained and given in Table 2.

Lastly, to validate the models, suspended sediment samples were collected from five monitoring gauging stations during the Belg rainy season of the year 2018. By using this newly measured data, the prediction error (%) of linear log–log, linear log–log with bias correction, and non-linear log–log regression methods were calculated. At the Maki monitoring station, the prediction error was +15,

+23.44, and −2.8; at Duguda Station −9.97, +18.68, and −1.96; Abura −19.89, +13.16, and +3.49; Fite −14.11, +15.87, and −2.45; and for Bulbula −3.59, −1.34, and −0.25. The non-linear least squares regression method gave an error below ±3.5%. For Bulbula Station, the error was similar for all of the methods. Therefore, for all monitoring stations, the non-linear log–log regression approach was used to estimate the sediment load of the rivers. This approach was also selected during the study carried out on the Mackinaw River at Congerville, Kankakee River near Wilmington, Sangamon River near Oakford, and Illinois River in the USA by Reference [43] to estimate their sediment budgets and by Reference [65] to assess the sediment balances in the Blue Nile River Basin.

#### 4.1.2. Predicted Sediment Concentrations in Each Monitoring Station

The estimated sediment yield by selected rating curve (non-linear regression method) for each monitoring station is given in Table 3. In this calculation, the daily mean stream flows were used to get daily sediment yields of each day.

**Table 3.** Overview of suspended sediment discharges from four gauged catchments in the Lake Ziway basin.

| River | Monitoring Station | Annual Sediment Yield (SY) in $10^3$ Tons |
|---|---|---|
| Katar (Upper monitoring station) | Fite | 928.58 |
| Katar (Lower monitoring station) | Abura | 726.04 |
| Maki (Upper monitoring station) | Duguda | 1480.45 |
| Maki (Lower monitoring station) | Maki | 1196.34 |

### *4.2. Suspended Sediment Load from the Ungauged Rivers*

The annual suspended sediment yield from ungauged catchments were estimated by establishing an empirical regression model that related sediment yield of the gauged stations to several catchment characteristics namely, drainage area, slope, and average annual rainfall amount (Figure 10).

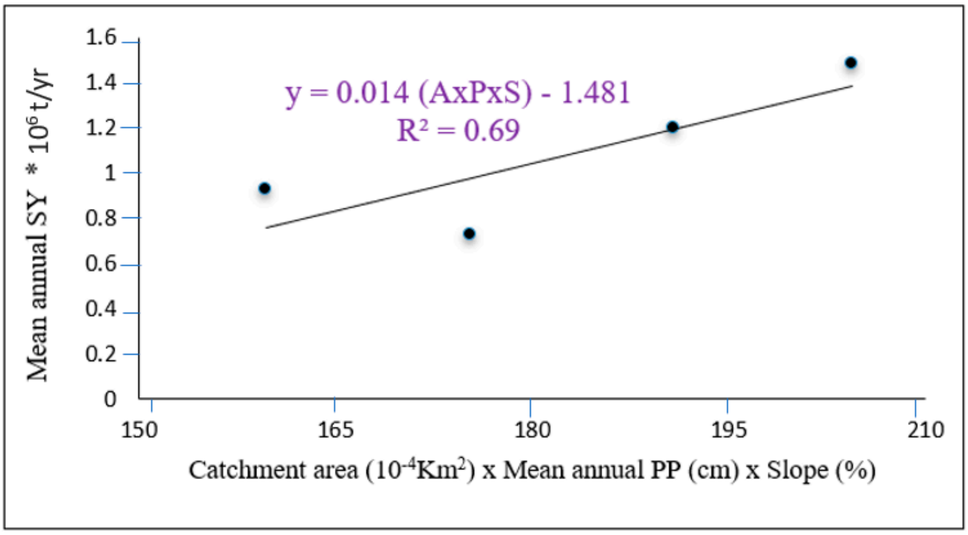


**Figure 10.** Relationship of mean annual SSY with the product of catchment area, slope, and average annual rainfall.

After model application to ungauged catchments, a total sediment yield of 0.16 million ton/year was obtained. Thus, this implies an area-specific sediment yield (SSY) for ungauged catchments (1460.64 km$^2$) as 111.55 ton/km$^2$/year. The reason for this low sediment yield for the ungauged part of the basin may be due to it gentle slope (on average 7%). But by using such approaches, study on Lake Tana basin by Reference [38] indicates as the best relationship was established to estimate the SY of the ungauged rivers by using an average annual rainfall and catchments area.

In most studies, to predict the sediment yield of ungauged catchments, the commonly used attribute is the catchment area only [66]. From other terrain attributes, area can easily be determined if maps of appropriate scale are available Some studies in Ethiopia, for example Reference [67] in Northern Tigray, used catchment area only to estimate the sediment yield of ungauged parts. Similarly, Reference [68] developed an equation that relates SSY with catchment area for the Central and Northern Ethiopian highlands (Equation (10)).

$$\text{SSy} = 2595\text{A}^{-0.29}\ (\text{n} = 20;\ \text{r}^2 = 0.59) \tag{10}$$

where SSy is area-specific suspended sediment yield in t $km^{-2}$ $year^{-1}$; A is area in $km^2$.

Furthermore Reference [68] suggested that in conditions where measurement of suspended and bedload sediment is not possible, a rough estimation of SSY for an "average" Ethiopian catchment could be derived based on Equation (10), and Reference [59] applied the suggested equation to model the sedimentation rate of Lake Tana.

Hence, in our study basin, the relation of sediment yield with contributing catchment area is inversely related, and similar observations have been reported by References [38,67,68]. But when we check the applicability of the suggested equation by Reference [68] for our study area, it overestimated the sediment yield predicted for ungauged catchments by a combination of slope, rainfall, and catchment area by 180%, i.e., for an ungauged area of 1460.64 $km^2$, the equation will give SSY of 313.63 ton/$km^2$/year, and hence, predicting SSY with an area-only based method is not preferred for estimating the sediment yield.

The bedload contribution of ungauged parts of the basin was not considered. Since the bedload comprises the sediment that moved downstream by saltation and rolling, it requires substantial flowing velocity. But, the ungauged parts of study basin are located in the lower position of the basin with flat to gentle slopes. Hence, it cannot generate a flow that can transport the sediment in the form of bedload.

### *4.3. Suspended Sediment Deposited in Floodplains*

The measured sediment discharges in both rivers show that the sediment yield of each upper monitoring station was larger than that of the corresponding lower station. On average 20.6% of the sediment load from hilly catchments was deposited in the floodplains and did not reach Lake Ziway (Table 4). This corresponds to an average aggradation rate of 19.2% for the Maki River and 22% for the Katar River, which indicates less deposition is occurring inside of the Maki sub-basin.

Reference [68] indicates the absence of any studies related to sediment deposition rates in floodplains in Ethiopia. Some studies in Northern Ethiopia, such as References [59,68], assumed 30% of the suspended sediment load to be deposed in floodplains. In the Kalaya River basin (Zambia), Reference [57] indicated the existence of 30% suspended sediment loss in floodplains. Similarly, Reference [69] estimated an overbank deposition of sediment on floodplains during flood events may range up to 40–50% of load delivered into the main channel system. Here on average, the floodplain storage rate of our study basin is lower than estimated for Northern and Central Ethiopia and the Kalaya River basin in Zambia.

### *4.4. Estimated Bedload*

For both tributary rivers, the bedload was calculated by assuming 10% of suspended sediment load and estimated as $174.36 \times 10^3$ ton/year. Before joining Lake Ziway, the two tributary rivers (Maki and Katar) flow down a gentle slope for more than thirteen kilometers. Hence the contribution of bedload by those rivers may be low and the predicted value may be reasonable.

**Table 4.** Sediment deposited on the floodplain and net sediment yield delivered to the lake.

| Main River (1) | Monitoring Station | | SSC $10^3$ ton/year | | River Length Km | | Rate of Floodplain Aggradation per km Length $10^3$ ton/year (8) = ((4) − (5))/(6) | % of Upper Station SSC in Lower Station (9) = 100 × ((4) − (5))/(4) | Net SY into Lake ($10^3$ ton/year) (10) = (5) − ((7) × (8)) |
|---|---|---|---|---|---|---|---|---|---|
| | Upper (2) | Lower (3) | Upper (4) | Lower (5) | Upper to Lower (6) | Lower to Lake (7) | | | |
| Maki | Duguda | Maki | 1480.45 | 1196.34 | 41.56 | 15.39 | 6.84 | 19.2 | 1091.11 |
| Katar | Fite | Abura | 928.58 | 726.04 | 37.46 | 13.60 | 5.41 | 22.0 | 652.51 |

*4.5. Suspended Sediment Exported Out of Lake*

The suspended sediment rating curve equation was developed for the measured suspended sediment concentration at the Bulbula River gauging station (Figure 8). Application of the rating curve equation resulted in an annual suspended sediment outflow of 14,331.8 tons. The outlets start to export more sediment when excess water leaves the lake in the middle of the rainy season.

*4.6. Sediment Budget and Deposition Rates of the Lake*

A net annual suspended sediment deposition of 2039.59 $\times$ $10^3$ tons could be calculated from the estimated influxes and outflows (Figure 11). Dividing this mass by the bulk density of sediment particles could give the equivalent volumetric deposition rate. Use of the calculated bulk density of 1.22 ton $m^3$ resulted in a volumetric suspended sediment deposition rate of 1.67 $\times$ $10^6$ $m^3$ per year. If this spread evenly over the depositional area of the lake bottom (423 $Km^2$ at 1637 msl) it would give an average thickness of 3.98 mm/year. When a constant annual rate is assumed, the lake will lose 1 m in 251.2 years. Which is higher than annual sediment deposition and lake depth loss rates estimated for Lake Tana by Reference [38] (1 m in 1000 years): [59] (1 m in 714.3 years), lower than the sediment deposition rate estimated for Lake Hawasa in Ethiopia (1 m in 83 years) by Reference [70], and almost similar with Lake Naivasha Kenya (1 m in 210 years) by Reference [71].

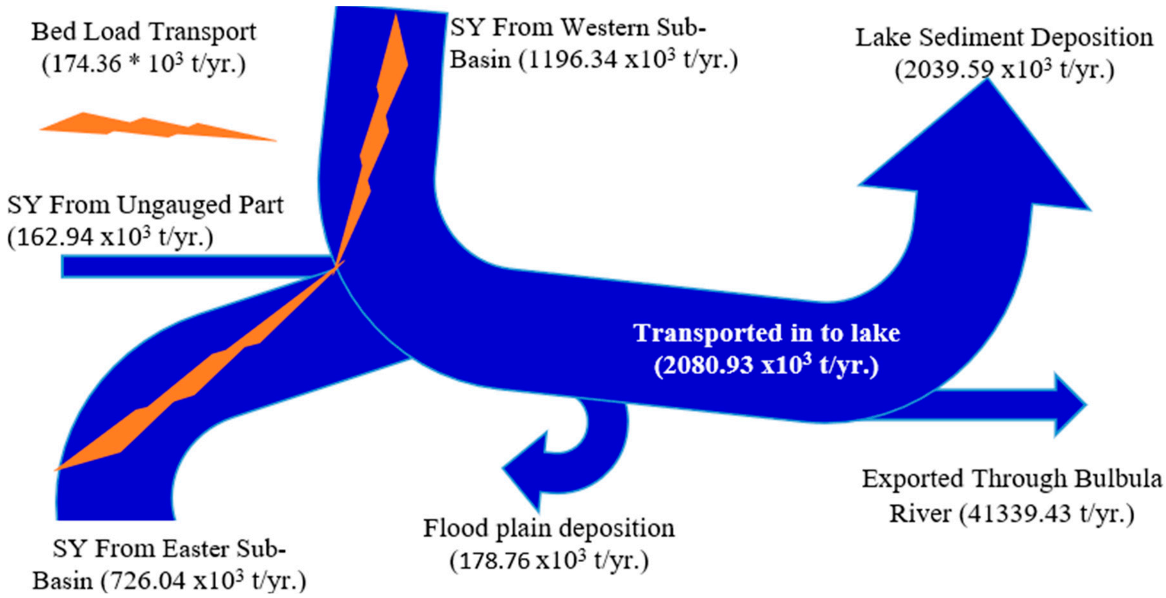


**Figure 11.** Sediment budget of Lake Ziway.

The sediment trap efficiency of Lake Ziway was also calculated from the estimated fluxes using Equation (9). The result indicated a trap efficiency value of 98%. Which is high compared with study done in Northern Ethiopia for Lake Tana. For Lake Tana, the sediment trap efficiency of 63% by Reference [38] and 88% by Reference [72] was predicted. The reasons for this high sediment trapping efficiency for Lake Ziway may be due to having a small discharge and position of outflow location. More sediment is entering into the lake from the north parts of the lake and the outflow location is on its southern corner. Moreover, for Lake Tana, there are two outlets namely the Blue Nile River and the Tana Beles tunnel for hydropower production. Hence, the calculated trapping efficiency of Lake Ziway is much greater than Lake Tana.

In terms of volume loss of the lake, the total accumulated rate of the sediment is 1.67 $\times$ $10^6$ $m^3$ per year and by taking the volume of the lake at elevation of 1637 msl (1580 $Mm^3$), the annual reduction in storage capacity could be estimated as 0.106%. With the estimated sediment deposition rate, it requires 9.47 years for the lake to lose 1% and 947 years to lose its total volume. Which is lower than the estimated global average rate for annual loss of reservoir capacity of 1% [73]. Similarly, the estimated per year volume loss of Lake Ziway is lower compared with Lake Tana by Reference [38] and for the Ethiopian Rift Valley Lake Hawassa by Reference [70].

### *4.7. Uncertainties in Sediment Budget Calculation*

Due to lack of instantaneous flow measurement, the sediment rating curve was developed based on daily average stream and sediment flow rates. Moreover, the estimated bedload accounts for 10% of the sediment entering into the lake through the main rivers, and which had not been directly measured in the studies. The floodplain deposition of the sediment is considered as uniform upon its length. The future lake sedimentation rates and its half-life is predicted by assuming the basin's rainfall pattern with constant trends. So, there may be uncertainties with this assumption.

## 5. Conclusions

In this study, sediment transport rates were estimated for five monitoring gauge stations by developing rating curves with normal linear log–log regression, normal log–log regression with correction bias factor, and non-linear log–log regression. The best-fit model was tested and evaluated qualitatively by time-series plots, quantitatively by using watershed model evaluation statistics, and validated by calculating the prediction errors. On tributary river monitoring stations, the non-linear log–log regression method estimated the sediment yield better than others, and for the lake out flow monitoring station, all methods predicted equally.

The model estimated the gross sediment load transported into the lake as $2080.93 \times 10^3$ ton/year. The sediment load exported out of the lake by the Bulbula River was 41,339.4 ton/year, and as a result, a net annual sediment mass of $2039.6 \times 10^3$ ton/year was deposited in the lake.

Though a uniform sedimentation pattern is unusual, the average deposition rates will have a depth of 3.98 mm/year on the lake bottom and the volume loss per year is 0.106%. The analysis shows a mean lake trapping efficiency of 98% and by assuming such a uniform sedimentation pattern, the expected half lifetime of the lake is 473.5 years.

**Author Contributions:** A.O.A. conceived the study. He has also participated in the design of the study, carried out the data collection, analysis of data, and performed the statistical analysis. A.M.M. and B.C. participated in the sequence alignment of the draft manuscript. They also participated in its design and coordination, and helped to draft and edit the manuscript. All authors read and approved the final manuscript.

**Funding:** The study was financed by Addis Ababa University Institute of Technology.

**Acknowledgments:** We would like to thank the Ethiopian National Meteorological Service Agency and Ministry of Water, Irrigation, and Electricity for providing the necessary data.

**Conflicts of Interest:** The authors declare no conflict of interest.

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