



**ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING**

A DISSERTATION ON:

**MODELING SEDIMENT YIELD, TRANSPORT AND DEPOSITION IN THE DATA
SCARCE REGION OF ETHIOPIAN RIFT VALLEY LAKE BASIN**

BY: ALEMU OSORE

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**MODELING SEDIMENT YIELD, TRANSPORT AND DEPOSITION IN
THE DATA SCARCE REGION OF ETHIOPIAN RIFT VALLEY LAKE
BASIN**

Ph.D. Dissertation

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**MODELING SEDIMENT YIELD, TRANSPORT AND DEPOSITION IN THE DATA
SCARCE REGION OF ETHIOPIAN RIFT VALLEY LAKE BASIN**

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By submitting this dissertation, I declare that the entirety of the work contained herein is my own, original work, that I am the sole author. The work contains no material that has been accepted for the award of any other degree in any university and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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ABSTRACT

Knowledge of sediment yield, transport and deposition processes taking place in a river basin is necessary to find suitable mitigation measures for reservoir sedimentation and to estimate lifespans of reservoirs. This research is undertaken to analyze the sediment yield of catchments, transport capacity of streams and sediment deposition rates and patterns in Lake Ziway Basin, Rift Valley Lakes Basin of Ethiopia; and to develop a sediment yield predication model by considering the soil, geomorphologic and hydrologic parameters of the basin.

Sediment yield of Lake Ziway Basin and sediment flux of the streams discharging into the Ziway Lake is modeled; and the sediment yield is estimated to be 2.081 Mt/year. Quantity of sediment that deposits in the floodplains, leaves the Lake through Bulbula River and that deposits in Ziway lake is estimated to be 0.178 Mt/year, 0.0413 Mt/year and 2.039 Mt/year, respectively. Based on the established sediment budget, Lake Ziway will lose its volume by 0.106% annually and its life-span is predicted to be 947 years. This result is validated by multi-frequency reservoir survey techniques using the lake bathymetry survey data obtained in 2005 and 2017. In the period of 12 years extending between the bathymetric surveys, 17.75 MCM (4.2cm average thickness) of sediment is deposited in the lake. Assuming a constant deposition rate in the period, the reservoir sedimentation rate is 1.81 Mt/year. This results in about 0.093% annual storage capacity reduction and 520 years expected half-life of the lake.

By using the SWAT model, soil erosion risk and hot spot erosion area of the basin is assessed. Soil conservation scenarios that reduce the slope length of the watershed by 50%, can decrease the sediment yield of the basin by 55%. As the soil erosion is the product of erosivity and

erodibility, an alternative soil erodibility estimation factor (KET) is derived from the soil data of the Ethiopian Rift Valley Lakes Basin (ERVLB) and has been evaluated for its applicability for soils found across Ethiopia. Statistical values of the analysis indicate that, the performance of KET is excellent for soils of ERVLB and acceptable within $\pm 5\%$ relative error for 35.7% of the soils across the country. Thus, KET values can be applied for soils found across Ethiopia with relative error and standard deviation of -9.88% and 6.4, respectively.

An empirical model is developed to estimate the sediment concentration of rivers in Ziway Lake Basin based on hydro-geomorphology and stream flow characteristics and tested for its applicability. Validation of the model showed an acceptable performance.

To conclude, this study provides an appropriate method to estimate the soil erodibility rate and sediment flow rate of the basin. Applying the method, high sediment risk area of the basin is identified. The method will be useful for concerned organizations to mitigate erosion rate at hot spots and at any part of the basin as necessary. The study has developed, the lake stage-volume-area relation which can be used for future water resource assessment studies.

" ሁሉ በእርሱ ሆነ፣ ከሆነውም አንዳች ስንኳ ያለ እርሱ አልሆነም " ዮሐ 1፥3

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LIST OF ACRONYMS

AMC	Antecedent Moisture Condition
ANGPS	Agricultural Non-Point Source Pollution Model
BD	Bulk Density
CN	Curve Number
DEM	Digital Elevation Model
Dg	Geometric Mean Diameter based model
EPIC	Erosion Productivity Impact Calculator
ERVLB	Ethiopian Rift Valley Lake Basin
FAO	Food and Agricultural Organization
GIS	Geographical Information Systems
GPS	Global Positioning System
HRUs	Hydrological Response Units
IDW	Inverse Distance Square Interpolation Method
K	Soil Erodibility Factors
KET	Alternative Soil Erodibility Method
MCM	Million Cubic Meter
MoWIE	Ministry of Water Irrigation and Electricity
MoWR	Ministry of Water Resource
Mt	Million tons
NSE	Nash-Sutcliffe Efficiency
OCC	Organic Carbon Contents
PBIAS	Percent Bias
R ²	Coefficient of Determination

RMSE	Root Mean Square Error
RUSLE	Revised Universal Soil Loss Equation
SCS	Soil Conservation Service
SSC	Suspended Sediment Concentration
SSY	Area-Specific Sediment Yield
SUFI-2	Sequential Uncertainty Fitting
SWAT	Soil and Water Assessment Tool
SWAT-CUP	A computer program for calibration of SWAT model
SY	Sediment Yield
TIN	Triangulated Irregular Network
USLE	Universal Soil Loss Equation
UTM	Universal Transverse Coordinate System
WWDSE	Ethiopia Water Works Design and Supervision Enterprise

1. INTRODUCTION

1.1. Background of the study

Sediment transport is an area of interest to developers, engineers, researchers and landowners because of its impacts on land and water bodies (Mahmood and Mundial, 1987; Petts and Gurnell, 2005). In the catchment, precipitation and surface runoff are the main factors which generate the sediment yield by detaching the soil particle (Reusser et al., 2015). These sediments reduce not only soil productivity but also reservoir capacity. Reservoirs around the world have been filled with sediment at a rate of approximately 1% to 2% per year (Abdallah and Stamm, 2012; Yoon, 1992) and their capacity and performance has been diminishing. Excessive sedimentation not only reduces the reservoir's volume and depth but also (Rădoane and Rădoane, 2005; Rahmani et al., 2018) impacts water quality, aquatic habitat, navigation, recreation, real estate values, and tourism. Similarly, in the tributary rivers, sediment deposits on the bed of the channels raises the bed level and enhances flood risks (Ali et al., 2014).

Estimating the sediment loads in the river basin is important to assess watershed management programs and to evaluate the effect of sedimentation on its water resources (Juliana and Melesse, 2015; Maalim and Melesse, 2013). The sediment budgeting of river basin comprises the identification and quantification of the sources, pathways and sinks of eroded material within a catchment (Slaymaker, 2003; Walling and Collins, 2008). At a basic conceptual level, a sediment budget consists of estimates of input [i.e. eroded soil or sediment yield (SY) transported into a depositional area], output (e.g. sediment load exported from a depositional

area) and the change in storage (Boukhrissa et al., 2013; Cigizoglu et al., 2002; Parsons, 2012).

The design and implementation of improved catchment-based erosion control and sediment management strategies are frequently hampered by the lack of data on both erosion rates and sediment yields, and an understanding of the processes associated with the delivery of fine sediment through the catchment system (Defersha and Melesse, 2012a, 2012b). Sediment yield provides an important index of land degradation, severity and trends, and also reflects the characteristics of a watershed, its history, development, use and management (Melesse and Abtew, 2015; Mohammed et al., 2015). Therefore, estimation of sediment yield is needed because it not only affects reservoir capacity, sediment transport to the lake, stream water quality and quantity, stream habitat, channel morphology and in brief environmental health impact assessment but also is a good indicator for the effectiveness of watershed management conditions (Cheng et al., 2013; Wang et al., 2015).

In the river basin, the sediment yields can be estimated by four methods. 1) calculating from suspended sediment data at gauging stations (Sadeghi and Saeidi, 2010; Ulke et al., 2009); 2) estimating by gross soil erosion and sediment delivery ratio (models) (Vente et al., 2013; Walling et al., 2001); 3) analyzing reservoir sedimentation data (De Vente et al., 2013; Haregeweyn, Melesse, et al., 2012), and 4) estimating using sediment transport equations (Demissie, 2004; Hajigholizadeh et al., 2018). Investigators like Ali et al. (2014); Boggs et al. (2001) and Wang et al. (2008) recommended to apply at least two methods simultaneously in a given study. Because, each method has its own limitation on predicating sediment yields of the basin. For example, the first method does not include bed load, whereas the last method does

not include wash load. Thus, these two methods underestimate the sediment load. Similarly, in quantifying both soil erosion and deposition rates, the sediment budgets estimated from the third method cannot indicate the actual soil loss rate of the catchment. Because, a fraction of the soil eroded within a basin will be deposited near the erosion area, at the foot of the slope, or on floodplains and channel beds (Awulachew et al., 2009; Nyssen et al., 2008), the remaining fraction will reach the river outlet (Walling et al., 1998) and will ultimately be deposited in water bodies, such as lakes. The second method will provide both sediment yield and decision-making tool in the application of relevant catchment soil conservation techniques. However, in case of developing countries like Ethiopia, it is cumbersome to obtain the required data for these methods (models) (Steenhuis et al., 2009). Therefore, it is advisable to check the performance of the models in such area by relating with other methods rather than directly applying for an estimation of soil loss (Verstraeten et al., 2003; Tilahun et al., 2014).

The direct measurement of sediment in the river gauging station is the most preferred and trusted method. But it is not always practical because it is expensive and laborious. One of the methods widely used to predict sediment loads for such data with an irregular intervals area is using of sediment rating curve (Asselman, 2000; Boukhrissa et al., 2013; Horowitz, 2003; Jansson, 1997; Khanchoul and Jansson, 2008). Today, sediment rating curve is commonly used to assess patterns and trends of sediment load in river systems. Warrick (2015) applied rating curves for trend analyses of Yangtze River China; Lee et al. (2015) for sediment load estimation in Algeria Mellegue River basin; Costa et al.(2017) to estimate Rhône River contribution for Lake Geneva siltation and Moges et al.(2015) to assess the sediment concentration rating for upper Blue Nile. In order to validate the sediment yield estimated by rating curves and to obtain the indicators for environmental changes like lake or reservoir

sedimentation, lake ecosystem functioning, life time of reservoirs (Awulachew, 2006; Dost and Mannaerts, 2008; Yesuf et al., 2012), bathymetric surveying method is the most accurate. To link the sources of sediment inside the watershed and provide both sediment yield and decision-making tool for catchment soil conservation techniques, using model is the most relevant (Bayabil et al., 2010; Melesse and Abtew, 2015; Mohammed et al., 2015; Msaghaa et al., 2014).

Estimation of sediment yield by using sediment transport equations in the stream channel considers suspended load or bed load or total load. Different sediment transport equations have been developed for different specific situation of river systems. For example, Blench (1969) and Lacey (1930) developed the equation that estimate the total load of sediment transported in the river-based regime approaches. Shen and Hung (1972) proposed the regression equation between total sediment transport capacity of the river based with an average falling velocity of sediment particles. A number of studies used bed load equations to estimate the bed load contribution to the sediment budget. These include bed-load formula by Schoklitsch (1934) that developed based on flume data with medium sediment size, Kalinske (1947) used bed-load formula that was developed based on continuity equation (bed load discharge is equal to the product of the average velocity of the particle in motion), Rottner (1959) used bed-load formula that express the bed-load discharge in terms of the flow parameters based on dimensional considerations and empirical coefficients by applying the regression analysis on stream bed roughness parameters, Einstein (1950) considered bed-load formula that developed by the concept of probabilities of particle motion and Laursen (1958) employed bed-load formula that computes the mean concentration of bed-materials discharge based on empirical relation of size fraction of bed material, mean grain diameters of sediment

particles, shear velocity and etc. The comparisons of those equations were published by [Brownlie \(1981\)](#); [SRHG \(2006\)](#); [Yang \(1984, 2003\)](#). The result of these studies indicates that computed sediment load or concentration from different sediment transport equations gave a vastly different results from each other and from field measurements. Hence, it may give fairly accurate results for engineering purposes, if the equation is applied to conditions similar to those from where the equation was derived. In present study basin, the availability of the required sediment data (laboratory result) is much limited and such formulas cannot be applied to model the sediment transport and depositions. Therefore, in this study, to model the basins sediment yield, transport and depositions, three different approaches were applied and validated.

1.2. Problem of the statement

For most Ethiopia Rift Valley Lakes (Hawassa, Abaya), sedimentation is identified as the main cause for fluctuation of the water-level ([Dadi, 2013](#); [Alemayehu et al., 2006](#)). The water levels of some of these lakes showed dramatic changes in the last few decades. Even though the assessment has not been undertaken on sedimentation rate of Lake Ziway, the impact of sedimentation for this lake may be severe than the other due to its shallow depth (average depth less than 2.5 meter). Additionally, in Rift Valley Lake Basin master plan study, two dams are recommended on its two tributary (Maki and Katar) rivers for small scale hydropower, irrigation and water supply uses. The life stage of reservoirs will depend on sediment accumulation rate in the dam. Besides the long-term sediment flux rate of the rivers and hotspot erosion area within the basin should be known to take an appropriate assumption during the detail design of the proposed structures and to control the most eroded areas of the basin.

Different from the other Rift Valley Lakes, Lake Ziway is the only turbid freshwater that is being used for multi-purposes like for irrigation, fishing, domestic water supply, transportation, recreation and feeding fresh water to Lake Abiyata through Bulbula River. Different studies on the long-term water balance of Lake Ziway were carry out by [JICA and OIDA \(2001\)](#), [Legesse \(2002\)](#), [Mazengia \(2008\)](#), [Dribssa \(2006\)](#); [Ayenew and Becht \(2007\)](#) and [Eresso \(2010\)](#). Land use/cover changes and the impact of climate change have also been studied by [Barth \(2012\)](#) and [Zeray et al. \(2007\)](#), respectively. Despite the number of studies and their importance, the effect of sedimentation on its water resources is not yet explicitly investigated. The catchment erosion rate of the basin and the sediment flux rate of lake's tributary rives are not assessed and no sediment estimation model/ equations were developed and recommended for the basin to handle the sediment problem of the basin.

1.3. Objectives of the dissertation

The general aim of this research is to model sediment yield, transport and deposition in Lake Ziway Basin. Even though the specific objectives are within the respective chapters, the following list compiles the overall objectives of the study.

- ☞ To determine the sediment budgets of the lake basin;
- ☞ To quantify the sediment deposition rates and pattern inside the lake by using multi-frequency reservoir survey techniques;
- ☞ To assess the susceptibility rates of the basin soil for water erosion and to develop an alternative empirical model to estimate the soil erodibility rates of Ethiopian Rift Valley Lake Basin Soils;
- ☞ To prioritize the lake basin based with the risk of soil loss and propose the most suitable control method using semi-distributed models; and

☞ To determine an alternative empirical model to estimate watershed sediment yield based on hydrology and geomorphology of the basin.

1.4. Dissertation structure

This dissertation contains eight chapters where the first two cover general introduction and description of the study area. The general introduction including the background of the study, problem of the statement and objectives while, the study area description chapter is devoted for understanding of the study area with the respect to location, climate, soil and geology, land uses and water resources. Following this, Chapter 3 presents an analysis of river sediment fluxes and lake sedimentation rates. In this chapter, river sediment flux and siltation rate of a lake was modeled using 1215 suspended sediment concentration samples collected from four rivers and a lake outlet stations. In Chapter 4, the sediment deposition rate and pattern were examined by using a multi-frequency reservoir survey technique. The lake bathymetry of the years 2005 and 2017 were used to detect sediment deposition rates and pattern inside the lake. In Chapter 5, the susceptibility of basin's soil for water erosion were investigated and an alternative soil erodibility estimation model was developed and its performance was tested and evaluated for overall country (Ethiopian) soils. Chapter 6 focuses on identification of erosion risk area of the basin. In this chapter, the hot-spots of sediment sources in the basin is traced and an appropriate controlling method was identified by testing different conservation scenarios. Chapter 7 presents results of newly developed sediment predication model based on hydrology and geomorphology of the lake basin. Finally, Chapter 8 gives the overall conclusion and recommendations of the study.

2. DESCRIPTION OF STUDY AREA

2.1. Location

The Rift Valley Lakes Basin is situated in the southern part of the country, encompassing the southern segment of the main Ethiopian Rift, stretching northeast- southwest just north from Lake Ziway via Lakes Abiyata, Langano, Shala, Hawasa, Abaya, Chamo and Chew Bahir up to the boarder with Kenya. It is generally bounded by 8°30' N and 4°25' N latitude and 36° 30'E and 39°30' E longitudes (Figure 2.1). The total surface area is approximately 53,000 km² and represents relatively one of the smallest basins in the country. It is bordered by the Awash River Basin in north and northeast, Omo River Basin in west, Genale Dawa River Basin and Wabi Shebelli River Basin in the east and northeast respectively and the Ethiopian-Kenya border in the south.

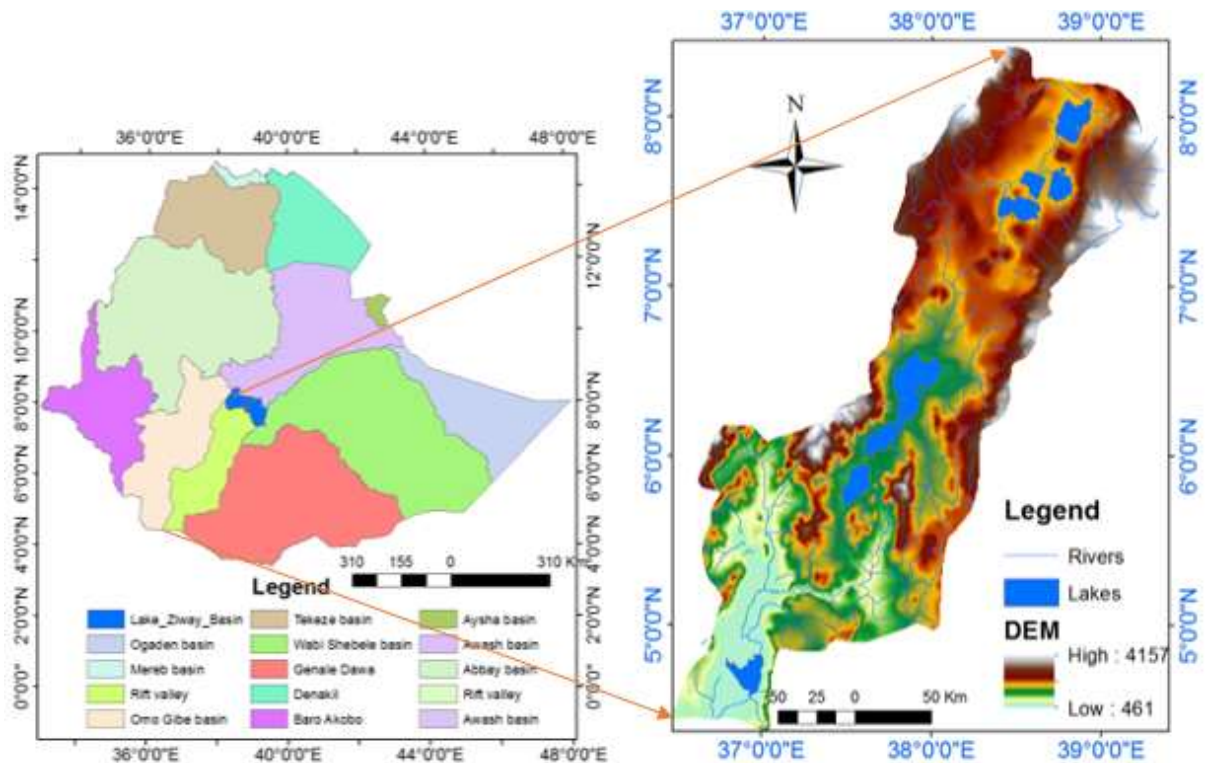


Figure 2. 1 Location Ethiopian Rift Valley in the country

Ziway Lake basin has a total area of 7285km² and geographically it extends from 7°20'54" to 8°25'56" latitude and from 38°13'02" to 39°24'01" longitude. There is a topographic difference of about 2600m between the rift floor and the high land areas (mountains). The basin is bounded in the east by Chilalo, Galama and Kakka mountains and in the west by Guraghe mountains (Figure 2.2).

The study lake, Lake Ziway, belongs to the central Ethiopian Rift Valley Lakes Basin. It has a maximum length and width of 32 and 20km, respectively. It has a surface area of 423km², maximum depth of 7.2m and average depth of 2.5m. Lake Ziway is the shallowest lake in the country and fills a depression at an elevation of about 1637m above-sea-level. It drains to Lake Abiyata. It is the third largest freshwater lake of the Ethiopian Rift Valley Lakes and the fourth largest of the freshwater lakes in Ethiopia. Inside the lake, there are five islands namely Gelila, Debre Sina, Tulu Gudo, Tsedecha and Fundro.

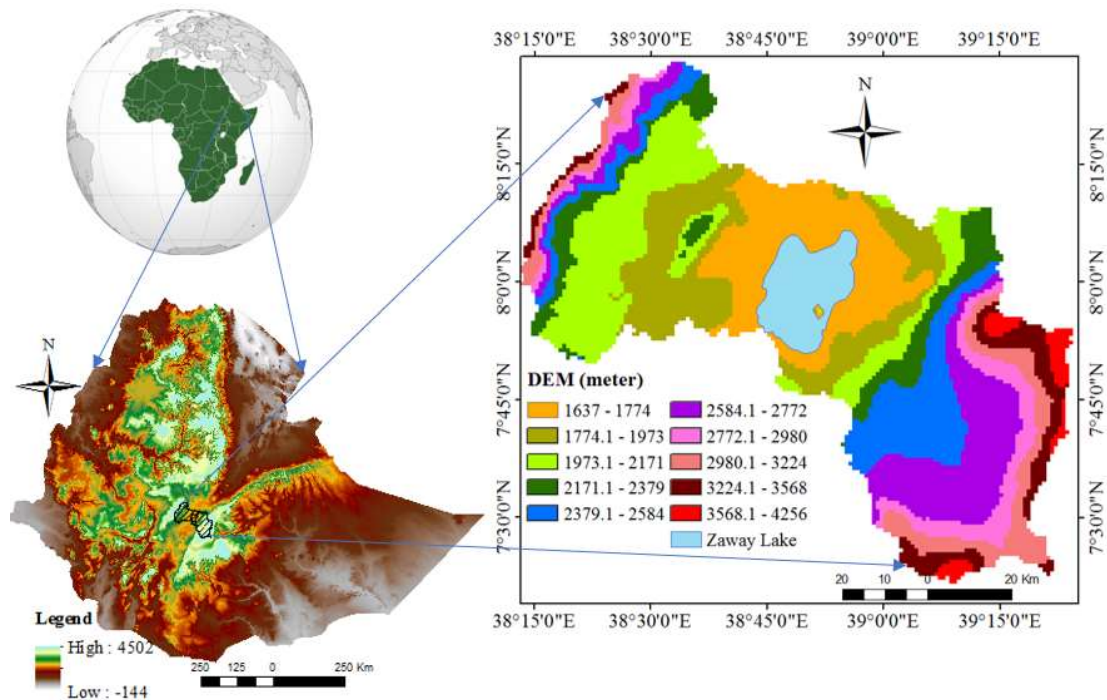


Figure 2. 2 Location of Lake Ziway Basin in Ethiopia Rift Valley

2.2. Climate and agro-ecology

According to [Ayenew \(2007\)](#) and [Scholten \(2006\)](#), the climate of 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. [Legesse \(2002\)](#) has classified the basin in three main seasons based on its rainfall. The long rainy season is summer which is locally known as Kiremt. The Kiremt rain represents 50 to 70% of the mean annual rainfall. The dry period is locally known as Bega which occurs when the line of low pressure ITCZ (Inter Tropical Convergence Zone) lies south of Ethiopia. It extends between October and February. The small rainy season known as *belg*, representing 20–30% of the annual rainfall, occurs during March to May when the ITCZ moves from south to north over the country. The time series plot of the long-term (1989–2016) average monthly rainfall on selected meteorological stations of the basin is shown in Figure 2.3 and confirms the above seasonal variations.

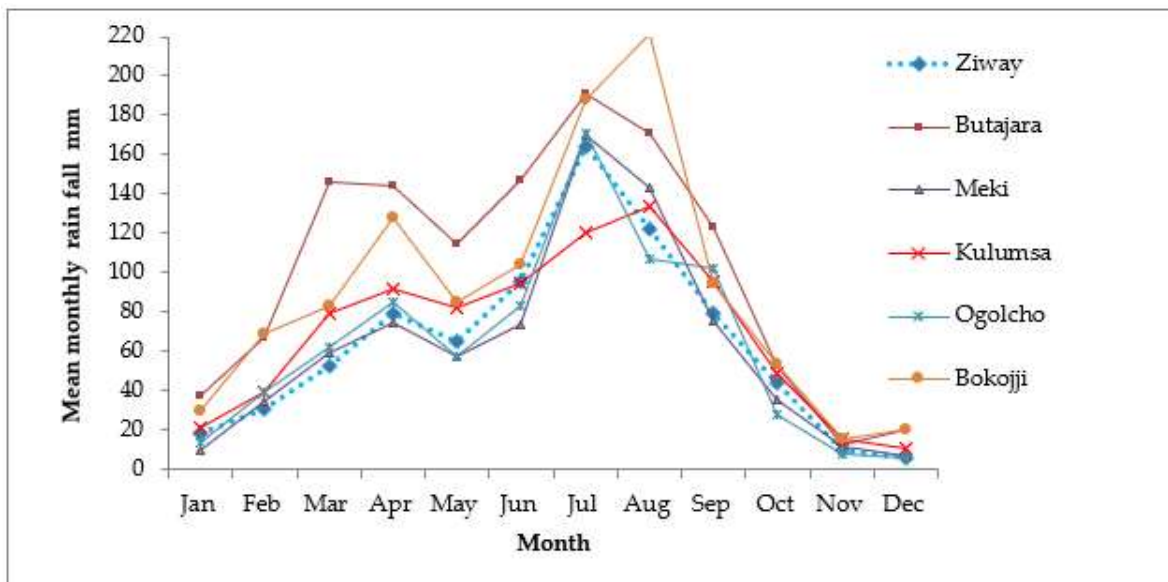


Figure 2. 3 Long-term (1989–2016) average monthly rainfall on selected meteorological stations

The long-term (1989–2016) mean annual-rainfall of Arata, Bekoji SF, Keteria Genet, Kulumsa, Meraro, Ogolcho, Adamitulu, Bui, Butajira, Koshe, Meki and Ziway meteorological stations ranges from 620 to 1225mm (Figure 2.4). The air temperature of the basin varies between 15 and 25°C.

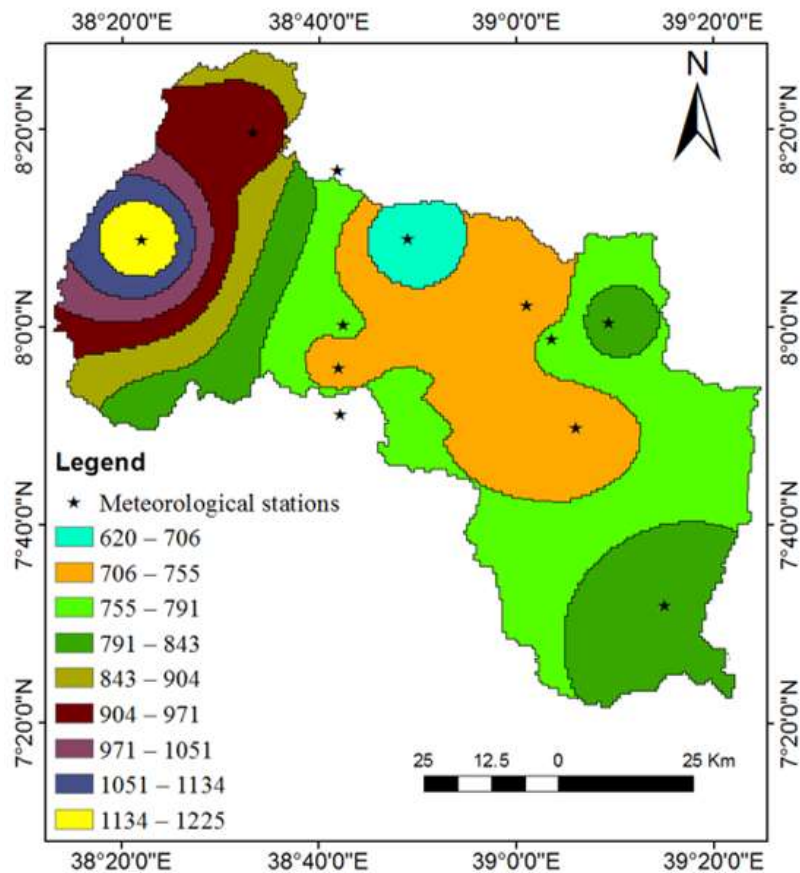


Figure 2. 4 Average annual rainfall depth (1987–2016) in Lake Ziway Basin based on inverse distance square interpolation method (IDW)- interpolation of data for near meteorological rain gauges stations

2.3. Soil

Eight soil types are identified in Ziway Lake basin by MOWR (2010) and is shown in Figure 2.5 and described in Table 2.1.

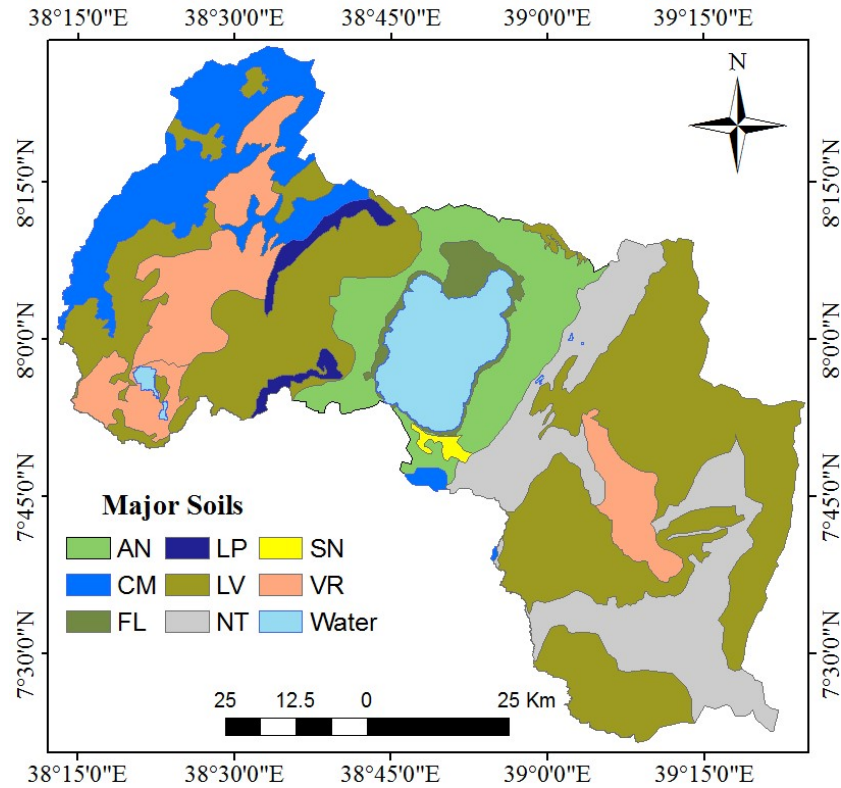


Figure 2. 5 Soil types of Ziway Lake Basin, Source: [MOWR \(2010\)](#).

Table 2. 1 Description of soil types of Lake Ziway Basin (Source: [MOWR , 2010](#))

Soil Type Code	Soil Type Description
Andosol (AN)	Deep to very deep, very dark grey to brown, medium and coarse textured, weak to moderate developed, fine and medium, crumb and sub angular blocky structure, very friable to friable; slightly sticky and none plastic, well to excessively drained.
Cambisols (CM)	Shallow to very deep; very dark grey to dark reddish brown; fine to coarse textured; moderate to strong developed fine to coarse, sub angular, granular and crumb structure; very friable to firm, none sticky to very sticky, none

	plastic to very plastic; well to excessively drained
Fluvisols (FL)	Moderately deep to very deep; black to dark yellowish brown; fine to coarse textured; Weak to moderate, fine and medium, granular and sub angular blocky structure; very Friable to firm, none sticky to sticky, none plastic to plastic; imperfectly to well drained
Leptosols (LP)	Very shallow; very dark grey to brown; coarse textured; weak to moderate, fine and medium sub angular blocky structure; Friable, slightly and slightly plastic; well to excessively drained.
Luvisols (LV)	Moderately deep to very deep; very dark grey to dark; fine and medium textured; moderate to strong, granular, crumb and sub angular blocky structure; very friable to firm, slightly sticky to sticky; slightly sticky to very sticky; moderately well to well drained.
Nitisols (NT)	Moderately deep to very deep; very dark brown to dusky red; fine and medium textured; moderate to strong, medium and coarse, sub angular blocky structure; very friable to slightly firm, sticky and plastic; well drained.
Solonetz (SN)	Deep to very deep; black to light olive brown; medium and coarse textured; moderate, medium and coarse sub angular blocky structure and massive in substrata, very friable, slightly sticky and slightly plastic; moderately well to well drained.
Vertisol (VR)	Deep to very deep; black to dark yellowish brown; fine textured, loam; moderate to strong, medium and coarse angular and sub angular blocky structure; firm to very firm, sticky and plastic; imperfectly to poorly drained.

2.4. Geology

The geology of Lake Ziway basin is divided into four major groups of rock units that are based on age-Precambrian to Early Paleozoic crystalline basement succession rock, Mesozoic sedimentary rock, Oligocene to middle Miocene pre-rift volcanic rock and middle-Miocene to Holocene syn-and post-rift volcanic rock and unconsolidated sediments (MOWR, 2010). These rock groups are different from one another by major unconformities with the exception that unconformable relationships are only manifested between pre- and post-rift deposits where faulting has caused tilting and subsequent erosion of the older rocks on blocks between zones of faults. The break in deposition may be marked by a hiatus without appreciable unconformity (MOWR, 2010).

2.5. Land use and land cover

In the basin, agriculture has long history. The basin as a whole is under intensive agricultural activity and different crops are grown in the region using both the *kiremt* and *belg* rains. In the rift floor, the main cultivated crops are maize (staple food in many parts of the region), *teff*, wheat and haricot beans while in escarpments and highland areas cereals are produced. The later are principal producers of cereals in the country (Legesse et al., 2004).

Ziway Lake basin experiences high population pressure and dynamic land use change (MOWR, 2010). There is intensive cultivation of land and this has extended to marginal lands; level of cultivation technology is low; and land management is poor (Ayenew and Becht, 2007; Barth, 2012; Dribssa, 2006; Eresso, 2010; Mazengia, 2008; MOWR, 2010; Zeray et al., 2006). This has resulted in severe soil erosion, soil fertility reduction and land degradation.

In the year 2010, the sediment delivery rate of the western sub-basin of the lake was assessed by MOWR (2010) and from the total basin around Considering the whole Ziway Lake Basin, 14% is highly eroded (SY = 50 to 106 t/ha/year) 24% is moderately eroded (SY = 20 to 50 t/ha/year) and the remaining 62% is slightly eroded (SY = 0 to 20 t/ha/year). Field data collection of this study identified severely eroded areas in Katar, eastern lake sub-basin.

2.6. Hydrology and morphology of Lake Ziway

Lake Ziway is located at 1637 masl which is relatively higher elevation than the other three central Ethiopian Rift Valley Lakes (Abiyata, Langanu and Shala). It is the largest and the shallowest lake lying in a shallow down-faulted basin flanked in the east by a large basalt field. Two main rivers Katar and Meki feed Lake Ziway and the lake overflows via Bulbula River to Lake Abiyata.

Katar River is the biggest perennial river that starts from Arsi high lands (Kakka Mountain). It flows northwest and joins the Lake Ziway. The river has a total watershed area of 3350 km² which ascends to over 4256 masl to the summits of Chilalo and Kakka mountains. The gradient of the river is generally steep throughout its course to Lake Ziway, and it is often deeply incised up to 50m below ground surface. The analysis of streamflow data obtained in the period 1989 to 2008 indicates, average annual runoff volume of Katar River flows to be 401.6 MCM.

Meki is another tributary river of Lake Ziway that drains an area of 2433 km² from the Gurage mountains to the west and northwest of the lake. Although the head water of Meki River is at an altitude of about 3500 masl, the river rapidly descends the rift valley escarpment to below 2000m before several major tributaries join it. Meki River is incised to a steep-sided valley

until it reaches Meki town at the head of its delta. Analysis of the stream flow data for the period from 1989 to 2008 indicates, an average annual runoff volume of contribution of 270.24 MCM to Lake Ziway.

The entire outflow from Lake Ziway is through Bulbula River, which flows in south direction to Lake Abiyata. Bulbula descends about 58m over 30km length between Lake Ziway and Abiyata. Lake Ziway is feeding Lake Abiyata with an average annual runoff volume of 116.3 MCM through Bulbula River. In addition to surface out flow, ground water flow from Lake Ziway to other central main Ethiopian Rift Lakes is expected since elevation of Lake Ziway is 1637 m, Langano 1585, Abiyata 1578m and Shalla 1550 m.

2.7. Existing and planned water resources development in Lake Ziway Basin

Lake Ziway basin is one of the highly irrigable basins of the country and several medium-scale irrigation schemes are being developed diverting water from the main rivers flowing into and out of the lake and from the lake surface, Table 2.2, (Shumet and Mengistu, 2016).

Table 2. 2 Existing irrigation development in Lake Ziway Basin

Sr. No	Water source	Irrigable Area (ha)	Irrigation Type	Owner
1	Katar River (@ Eastern of Lake Ziway)	858	Gravity & Pump	Community
2	Maki River (@ Western of Lake Ziway)	388	Gravity & Pump	Community
3	Lake Surface	2000	Pump	Private & community
4	Bulbula (lake outlet)	1095	Gravity & Pump	Private & community

Source: Fekadu (2016) and Shumet and Mengistu (2016)

Potentially suitable land for irrigation in Maki and Katar sub-basins are estimated as 214,580 ha and 152,200 ha, respectively (MOWR, 2010). However, the availability of water resources is limited and two dams, namely Lower Meki dam and Katar Ashebeka dam, are proposed to be construct on both rivers (MOWR, 2010).

The lower Maki dam site is geographically located from 904240N latitude to 459930E longitude in universal transverse mercator (UTM) coordinate system. The catchment area of the dam is 1690 km² and the mean annual flow estimated is 7.8 m³/s. The dam is proposed to provide head and seasonal storage for irrigation and hydropower generation (MOWR, 2010). Similarly, the dam site at Katar River is located from 852100N latitude to 517100E longitude. The Katar Ashebeka dam catchment area is approximately 1260 km² and is proposed to provide head and seasonal storage for irrigation.

3. ANALYSIS OF RIVER SEDIMENT FLUXES AND LAKE SEDIMENTATION ¹

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. The contribution of ungauged basin was estimated by developing a model that included the terrain attributes and measured sediment yield (SY). The bedload of the rivers were estimated and the total amount of sediment transposed in to the lake was calculated as 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. As the result, the net sediment deposition rate of the lake was estimated as 2.039 Mton/year and its trapping efficiency was 98%. Accordingly, the lake is losing its volume by 0.106% annually and the half-life of the lake is estimated as 474 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 Alemu O. Aga, Assefa M. Melesse and Bayou Chane (2019). Estimating a Sediment Flux and Budget of a Data Limited Rift Valley Lake in Ethiopia. *Hydrology*, 6 (1); PP1-23; [doi:10.3390/hydrology6010001](https://doi.org/10.3390/hydrology6010001)

3.1. Introduction

Sedimentation caused by catchment erosion is reducing a significant proportion of the original storage capacity of many lakes (Abdallah and Stamm, 2012). 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 (Asselman, 2000) and the benefits, lifespan, and the sustainability of lakes can be controlled by sedimentation (Wisser et al., 2013). Estimating the sediment loads of lake basins is important to assess lake siltation, identify sediment source areas, plan watershed management programs and evaluate the effect of sedimentation on water resources (Slaymaker, 2003; Walling and Collins, 2008; Kim et al., 2014). Sediment budget estimation of watersheds will require identifying major sediment sources (upland erosion, gully or channel erosion, riverbank erosion and also river bed contributions) (Cheng et al., 2013; Hajigholizadeh et al., 2018).

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. For a river basin, the sediment yield can be obtained by calculating from sediment data at gauging stations (Sadeghi and Saeidi, 2010); analyzing reservoir sedimentation data (Mhired et al., 2016); estimating using sediment transport equations (Hajigholizadeh et al., 2018) and or predicting with models (Abtey and Melesse, 2016; Defersha and Melesse, 2012a; Maalim and Melesse, 2013; Mekonnen and Melesse, 2011; Melesse et al., 2011; Msaghaa et al., 2014; Setegn et al., 2010). 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 (de Vente et al., 2013; Tilahun et al., 2014). 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 (Moges et al., 2018; Yesuf et al., 2012, 2013), 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) (Wischmeir, 1965) and its derivatives. However, in the case of developing countries like Ethiopia, it is cumbersome to obtain the required data for these models (Steenhuis et al., 2009). 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 (Asselman, 2000).

Today, a rating curve is commonly used by engineers and scientists for various purposes (Wang et al., 2008). 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 (Syvitski et al., 2000). For example, a rating curve has been applied to the Yangtze River, China, for trend analyses (Warrick, 2015); for sediment rating curve modification of the Marun Dam, Iran (Bordbar and Fuladipanah, 2014); for sediment load estimation in Algeria in the Mellegue River Basin (Lee et al., 2015), to estimate the Rhône River contribution for Lake Geneva (Costa et al., 2017); to assess the sediment concentration rating for the upper Blue Nile (Moges et al., 2015); and to revise lake sediment budgets of Lake Tana, Ethiopia (Lemma et al., 2017).

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 (Alemaw et al., 2016; Ayele et al., 2017), 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). Yet it serves in such a way, studies indicate that, the predicted suspended sediment load from sediment rating curve techniques is either underestimating (Asselman, 2000; Demissie, et al., 2004) or overestimating (Achitea and Ouillon, 2007) 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 (Ferguson, 1986) and using non-linear regression methods (Demissie et al., 2004). Even though there are different compensation methods employed to develop a sediment rating curve, none of them have received universal acceptance (Sadeghi and Saeidi, 2010). 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. [Harrington and Harrington \(2013\)](#) 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. Moreover, according to [MOWR \(2010\)](#) 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 chapter are:

- To develop the best fit rating curves to estimate suspended sediment loads;
- To estimate overbank sedimentation on floodplains of Lake Ziway tributary rivers; and
- To establish a sediment budgets of the lake.

3.2. 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 3.1.

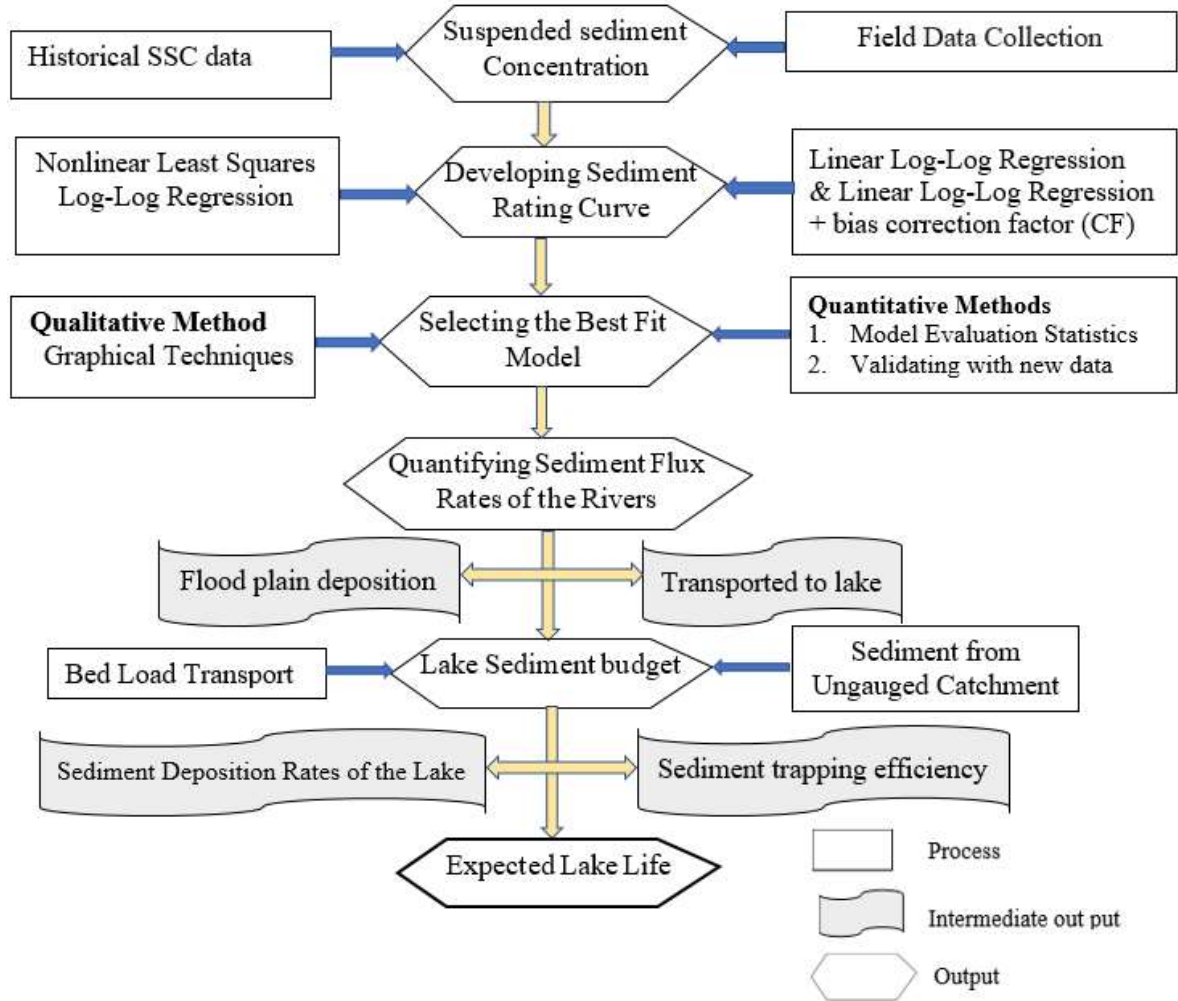


Figure 3. 1 The work flow diagram used for the study

3.2.1 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 3.2) 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.

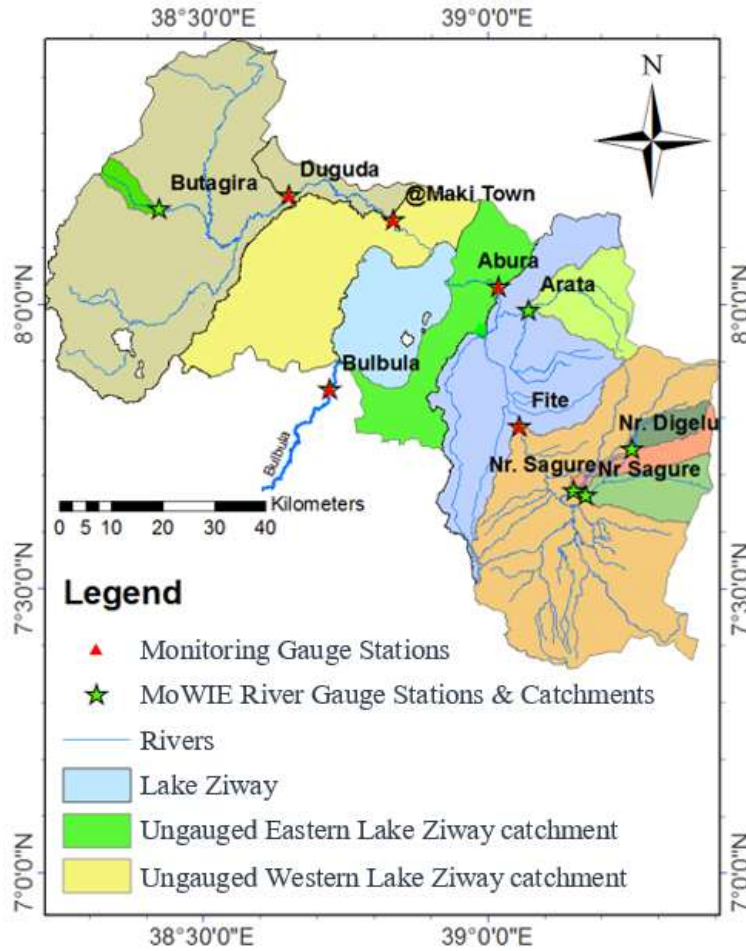


Figure 3. 2 Ziway Lake Basin river monitoring gauge stations collected MoWIE

3.2.2 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 [Edwards and Glysson \(1988\)](#). 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 ([American Society of Testing and Materials, 2007](#)). 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 [Ongley and Nations \(1996\)](#).

The river cross-sectional profile was assessed in low- and medium-flow seasons using a few hydrological apparatuses (total-station and measuring tape) 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.

3.2.3 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 ([Zhang et al., 2004](#)) and is equated as:

$$\text{Log } (Q_s) = a + b * \text{Log } (Q_w) \quad (3.1)$$

where Q_s 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 (Ferguson, 1986). A bias correction factor (CF) was introduced and the SSC rating curve was corrected as:

$$\text{Log (Qs)} = a + b * \text{Log (Qw)} + \text{CF} \quad (3.2)$$

Ferguson (1986) proposed a statistical bias correction factor (CF) equal to $\exp(2.65S^2)$ to reduce the degree of underestimation by rating curve with

$$S^2 = \frac{\sum_{i=1}^n (\text{Log (Ci)} - \text{Log (\hat{C}i)})^2}{n-2} \quad (3.3)$$

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:

$$\text{Log (Qs)} = a + b * (\text{Log Qw})^c \quad (3.4)$$

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 Asselman (2000).

By using those three methods (Equations (3.1), (3.2), and (3.4)), 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 four widely used statistics namely: coefficient of determination

(R²), 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 3.1 (Moriasi et al., 2007; Qi, et al., 2017).

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

$$\text{Error (\%)} = \frac{(\text{Rating Curve Estimate} - \text{Measured value})}{\text{Measured value}} \times 100\% \quad (3.5)$$

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

Table 3. 1 General performance ratings for recommended statistics to evaluate models

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)	($-\infty$ –0.5)
$RSR = \frac{\sqrt{\sum_{i=1}^n (SSC_i^{obs} - SSC_i^{Sim})^2}}{\sqrt{\sum_{i=1}^n (SSC_i^{obs} - SSC_{obs}^{mean})^2}}$	(0–0.25)	(0.25–0.5)	(0.5–0.6)	(0.6–0.7)	(0.7– $+\infty$)
$PBIAS = \frac{\sum_{i=1}^n (SSC_i^{obs} - SSC_i^{Sim}) * 100}{\sum_{i=1}^n (SSC_i^{obs})}$	(0– ± 5)	(± 5 – ± 15)	(± 15 – ± 30)	(± 30 – ± 55)	(± 55 – $\pm \infty$)

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

3.2.4 Suspended sediment load deposited on floodplains

Floodplain upstream of the lakes can serve as sediment trapping areas as large alluvial soils can be deposited by rivers (Walling et al., 2001). The two tributaries of Lake Ziway drain large part of a floodplain (Figure 3.3) which retain most of the sediment transported and used as site for intensive sand mining activities across sections of the rivers (EFDRRVLA, 2016).



A. Floodplain area at the lower Maki River



B. Sand mining activities from river sections

Figure 3. 3 Floodplain deposition and sand mining activities across the river sections

In the lake basin, the sediment trapped in the floodplain is a yield for the basin but it is not the budget for the lake, which needs to be quantified. To do this, the suspended sediment concentrations were collected on the lower and upper gauging stations of the two tributary rivers (Maki and Katar). For the case of Maki, the gauging stations Duguda and Maki were selected and for Katar, Fite and Abura gauging stations were selected. The length between the two gauging stations Duguda and Maki were 41.6 km and between Fite and Abura it is around 37.5 km. To estimate the sediment deposited on the river channels per length, the sediment yield estimated in the upper gauging station is deducted from the lower gauging station and divided by the river channel length as

$$\text{Sediment Loss Per Length} = \frac{\text{Load of upper gauging station} - \text{lower gauging station}}{\text{The length of the river reach between the two gauge}} \quad (3.6)$$

Lastly, to estimate the net amount of sediment transported in to the lake, the average per length loss rate calculated in Equ. 3.6 is multiplied by the distance between the lower station and the lake.

3.2.5 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 2.2). Hence, the contribution of ungauged basin was estimated by developing an empirical model that relates the terrain attributes namely drainage area, slope, and average annual rainfall with sediment yield [6]. From this, the three explanatory factors, the area and slope of the ungauged basins were extracted from the 30x30 DEM of the basin and mean annual rain fall was determined from the basin areal rainfall depth map (Figure 2.4).

3.2.6 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, 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.

3.2.7 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 (Delmas et al., 2012; Engida, 2010; Vanmaercke et al., 2014). In most rivers, bed load to suspended load ratio is in the range of 10% to 30% (Church, 2006), and in mountain rivers (high slope) ranges up to 35% of the suspended load (Sitaula et al., 2007). In this study, the Maki and Katar rivers flow on gentle slopes for more than thirteen kilometers before joining Lake Ziway. Hence, it is taken as 10% of suspended sediment load. In literature, similar estimation was done for Ethiopian river basins by Lemma et al. (2017) and Engida (2010), in other regions of the world by Akraasi (2005); Boateng et al. (2012); Phillips and Slattery (2006); Vörösmarty et al. (2003) and Walling (1984).

3.2.7 Sediment budget of Lake Ziway

Sediment balance for a lake Ziway is based on the law of conservation of mass (Nyssen et al., 2008)

$$\Delta V = SS_{in} - SS_{out} \quad (3.7)$$

where ΔV is the volume of sediment deposited inside the lake, SS_{in} the amount of sediment transported into the lake and SS_{out} is the amount of sediment exporting from the lake.

For the case of lake Ziway, the net amount of sediment interning in to the lake can be calculates as:

$$SS_{in} = SS_g + SS_u + SS_b \quad (3.8)$$

Were SS_g and SS_u stands for gauged and ungauged basins sediment flow and SS_b stands for bedload sediment flow.

3.2.8 Sediment volume and lake sediment trapping 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 t/m³ was determined.

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

$$Tef(\%) = \frac{(SY_{in} - SY_{out})}{SY_{in}} \times 100 \quad (3.9)$$

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

3.3. Result and discussion

3.3.1 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 $3.5 (\pm 4.8) \times 10^3$

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. For all monitoring stations, the suspended sediment concentration was decreasing after the end of main rainy season (September) and increases at the beginning of the small rainy season (Belg). During most dry seasons, the tributary rivers carry less sediment and a clear trend in mean sediment yield was observed. This seasonal suspended sediment flow pattern observed in the basin is similar to those found by a study done in Northern Ethiopia by [Lemma et al. \(2017\)](#) on tributaries of Lake Tana and by [Zenebe et al. \(2013\)](#) in Geba catchment northern Ethiopia.

3.3.1.1 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 (3.1)), normal linear log–log regression with correction factor (Equation (3.2)), and non-linear least squares regression (Equation (3.4)) methods were established for all monitoring gauging stations (Figure 3.4).

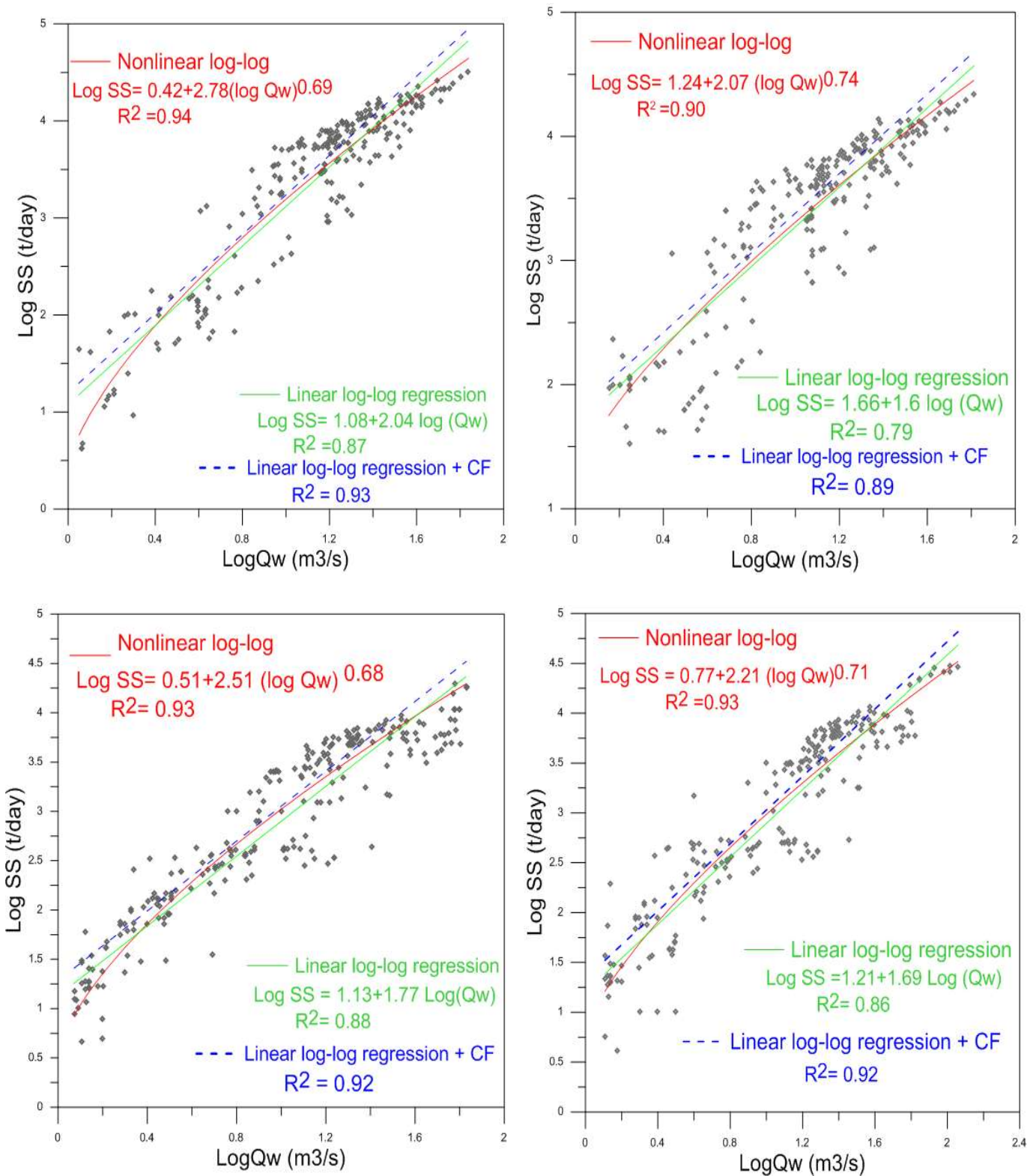


Figure 3. 4 The developed rating curves at station Duguda (upper left), Maki (upper right), Abura (lower left) and Fite (lower right)

The comparison plots between measured and computed data with three different rating curves, namely rating curve developed by normal linear log-log regression (Equation (3.1)), normal linear log-log regression with correction factor (Equation (3.2)), and non-linear least squares regression (Equation (3.4)) is shown in Figure 3.5.

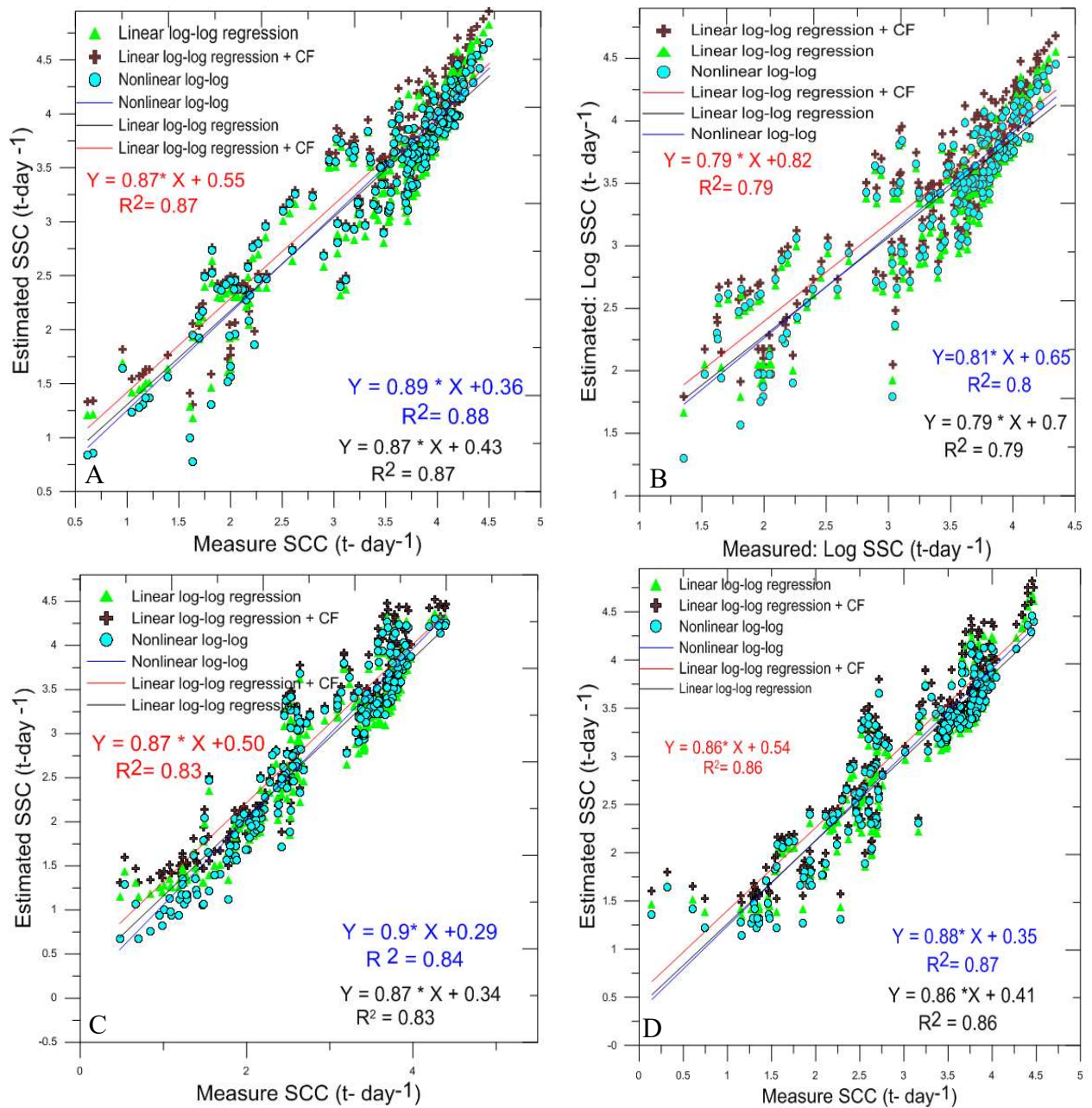


Figure 3. 5 Predicated and observed SSC at station; A. Duguda, B. Maki, C. Abura and D. Fite

Similarly, for the lake outlet station (Bulbula River), the sediment rating curve was developed as shown in Figure 3.6 A by using Equations (1), (2), and (4), and the comparison plot between measured and computed data is shown in Figure 3.6 B.

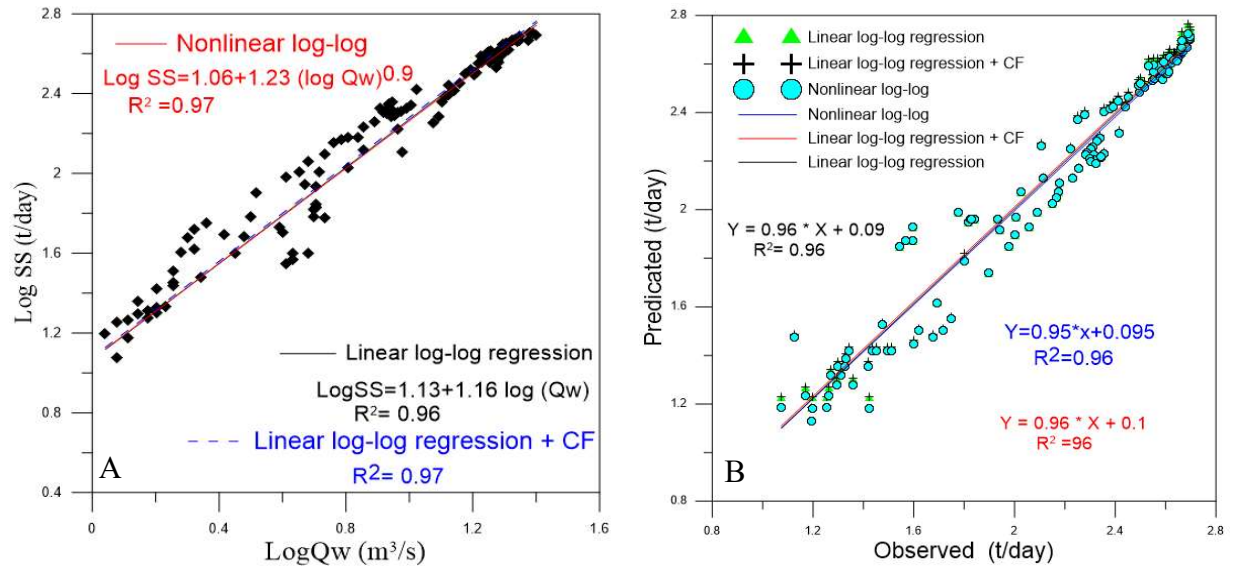


Figure 3. 6 A) The developed rating curves, and B) Predictated and observed SSC for station Bulbula

As shown in Figure 3.4, 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 3.4 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 3.4. As shown in Figure 3.4, 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 3.2)

Table 3. 2 Developed rating curves for rivers monitoring stations

Rating Curve		Stations				
		Maki	Duguda	Abura	Fite	Bulbula
Linear log-log Regression $\text{Log (SS)} = a + b * \text{log (Q}_w)$	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
Linear log-log Regression + CF $\text{Log (SS)} = a + b * \text{log (Q}_w) + \text{CF}$	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
Non-Linear log-log Regression $\text{Log (SS)} = a + b * (\text{log Q}_w)^c$	R ²	0.9	0.94	0.93	0.93	0.97
	NSE	0.8	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

The outperformed model was selected based on minimum RSR and PBIAS, and maximum NSE and R². [Moriassi et al. \(2007\)](#) recommended that if the R² 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, 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 3.4.

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 3.6 and Table 3.2). As shown in Figure 3.6, 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 3.7). 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 [Sadeghi and Saeidi \(2010\)](#) advise to use any method to develop sediment rating curves.

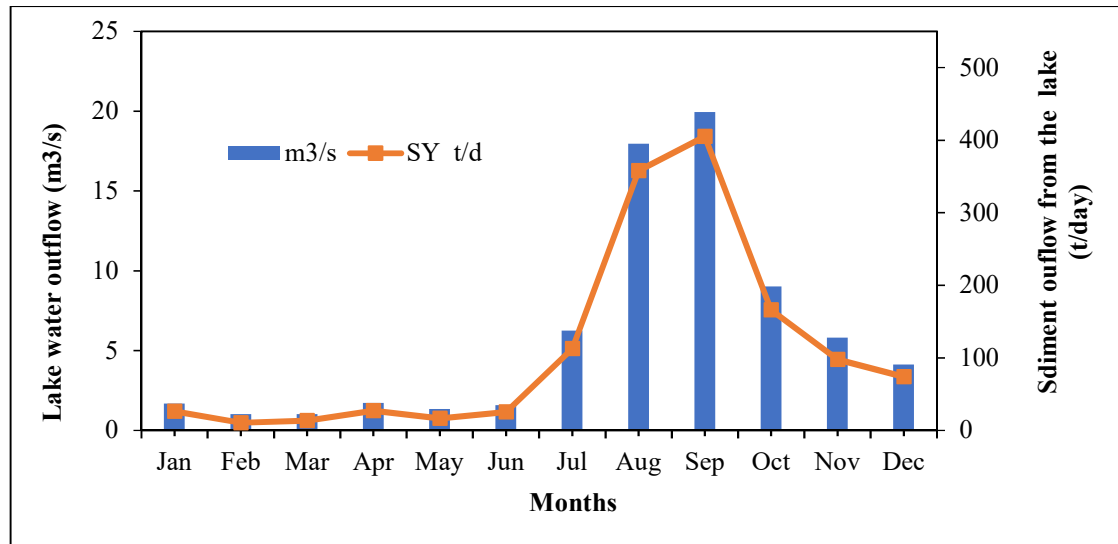


Figure 3. 7 Monthly variation of mean suspended sediment concentration (SSC) and lake outlets

By applying the developed models, the correlation of predicted and observed sediment were tested by slope and y -intercept values (Figure 3.5). 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 3.2.

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 $\pm 3.5\%$. 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 [Demissie, et al. \(2004\)](#) to estimate their sediment budgets and by [Ali et al. \(2014\)](#) to assess the sediment balances in the Blue Nile River Basin.

3.3.1.2 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 3.3. In this calculation, the daily mean stream flows were used to get daily sediment yields of each day.

Table 3. 3 Overview of suspended sediment discharges on four gauging stations

Monitoring station	Area (km ²)	Annual (2016 to 2017) sediment yield (SY) in 10 ³ tons
Fite	1982	928.58
Abura	3225	726.04
Duguda	1945	1480.45
Maki	2049	1196.34

3.3.2 Suspended sediment load from the ungauged rivers

The contribution of ungauged basin was estimated by developing a model that relates the gauged stations terrain attributes namely drainage area, slope, and average annual rainfall with annual suspended sediment yield (Figure 3.8).

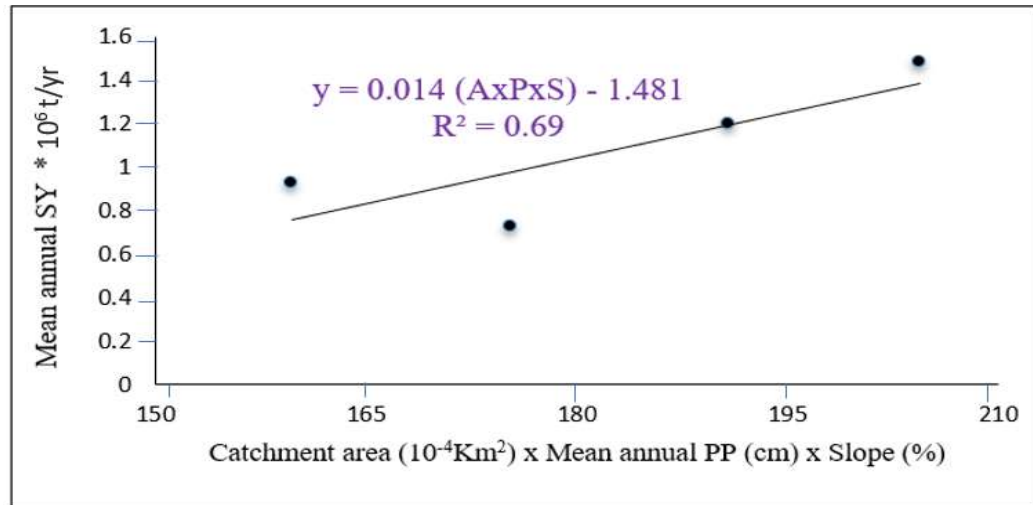


Figure 3. 8 Relationship of mean annual SSY of with the product of catchment area, slope and average annual rainfall

For ungauged catchments, the model estimates the mean annual suspended sediment yield of 0.16 million ton/year. Thus, this implies an area-specific sediment yield (SSY) for ungauged catchments (1460.64 km²) as 111.55 t/km²/year. The reason for this low sediment yield for the ungauged part of the basin may be due to its gentle slope (on average 7%).

In most studies, to predict the sediment yield of ungauged catchments, the commonly used attribute is the catchment area only (Lahlou, 1988). From other terrain attributes, area can easily be determined if maps of appropriate scale are available. Some studies in Ethiopia, for

example [Tamene et al.\(2006\)](#) in Northern Tigray, used catchment area only to estimate the sediment yield of ungauged parts. Similarly, [Nyssen et al. \(2004\)](#) developed an equation that relates SSY with catchment area for the Central and Northern Ethiopian highlands (Equation 3.10).

$$SSY = 2595A^{-0.29} \quad (n = 20; r^2 = 0.59) \quad (3.10)$$

where *SSY* is area-specific suspended sediment yield in t km⁻² year⁻¹; *A* is area in km²

Furthermore [Nyssen et al. \(2004\)](#) 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 [Engida \(2010\)](#) 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 [Lemma et al. \(2017\)](#); [Nyssen et al., 2004](#) and [Tamene et al. \(2006\)](#). But when I check the applicability of the suggested equation by [Nyssen et al.\(2004\)](#) for the 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 km², the equation will give SSY of 313.63 t/km²/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

3.3.3 Suspended sediment deposited in floodplains

A net annual suspended sediment deposited in the floodplains was estimated as 178.76×10^3 tone/year. This corresponds to 20.6% of total sediment yield of the basin (Table 3.4). The result indicates that as the average sediment aggradation rate along the Maki River and Katar were about 19.2% and 22%, respectively.

Nyssen et al. (2004) indicates the absence of any studies related to sediment deposition rates in floodplains in Ethiopia. Some studies in Northern Ethiopia, such as Nyssen et al.(2004) and Engida (2010), assumed 30% of the suspended sediment load to be deposited in floodplains. In the Kalaya River basin (Zambia), Walling et al. (2001) indicated the existence of 30% suspended sediment loss in floodplains. Similarly, Walling and Horowitz (2005) 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. Therefore, the suspended sediment deposited on the floodplain of our study basin is lower than what estimated for Kalaya River basin in Zambia and Lake Tana basin in Ethiopia.

Table 3. 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

3.3.4 Estimated bed-load

For both tributary rivers, the bedload was calculated by assuming 10% of suspended sediment load and estimated as 174.36×10^3 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.

3.3.5 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 3.6A). 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.

3.3.6 Sediment budget and deposition rates of the lake

A net annual suspended sediment deposition of 2039.59×10^3 tons could be calculated from the estimated influxes and outflows (Figure 3.9). 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 t/m^3 resulted in a volumetric suspended sediment deposition rate of $1.67 \times 10^6 \text{ m}^3$ 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 [Lemma et al. \(2017\)](#) (1 m in 1000 years): [Engida \(2010\)](#) (1 m in 714.3 years), lower than the sediment deposition rate

estimated for Lake Hawasa in Ethiopia (1 m in 83 years) by Belete (2013), and almost similar with Lake Naivasha Kenya (1 m in 210 years) by Rupasingha (2002).

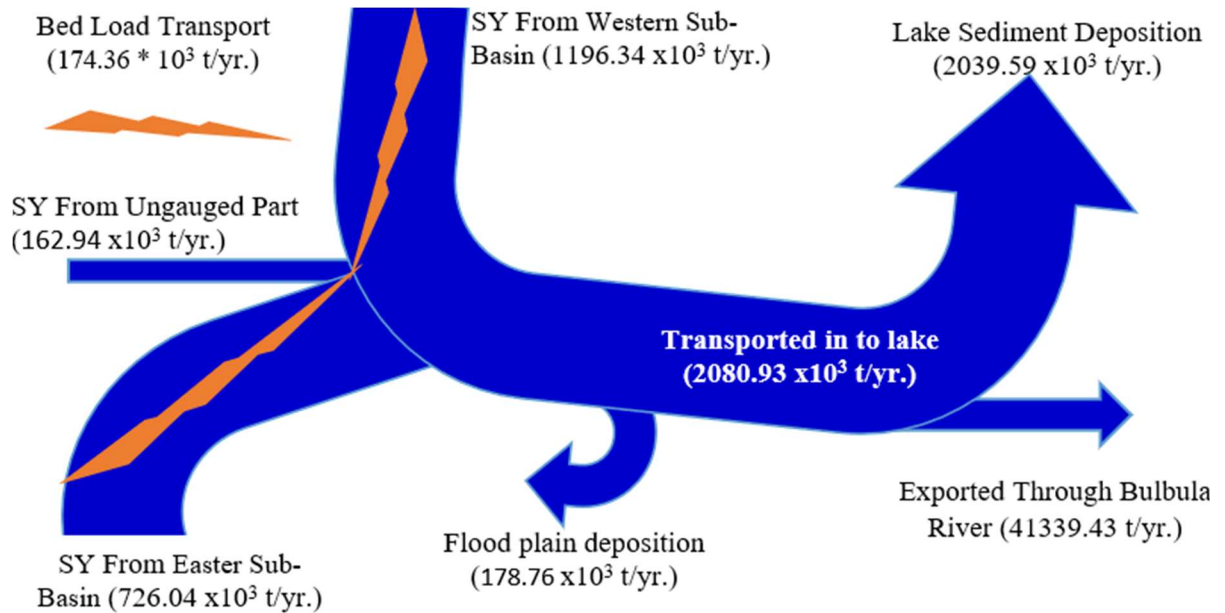


Figure 3. 1 Sediment budget of Lake Ziway

The sediment trap efficiency of Lake Ziway was also calculated from the estimated fluxes using Equation 3.9. The result indicated a trap efficiency value of 98%. This corresponds to sediment trap efficiency obtained for Lake Tana Ethiopia (96%) by Zimale et al.(2016). However, it is higher estimated by Engida (2010); 80%, SMEC (2008); 85% and Maes (2012); 91% for the Lake Tana.

In terms of volume loss of the lake, the total accumulated rate of the sediment is $1.67 \times 10^6 \text{ m}^3$ 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% (Douglas et al., 2001). Similarly, the estimated per year volume loss of Lake Ziway is lower compared with Lake Tana by Lemma et al. (2017) and for the Ethiopian Rift Valley Lake Hawassa by Belete (2013).

3.3.7 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.

3.4. Conclusion

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 2080.93×10^3 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 2039.6×10^3 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.

5. EVALUATING THE SUSCEPTIBILITY OF BASIN'S SOIL FOR EROSION AND DEVELOPING AN ALTERNATIVE SOIL ERODIBILITY APPROACH FOR ESTIMATION ²

ABSTRACT

Soil erodibility (K-factor) is an essential factor for erosion prediction, conservation planning and for assessment of sediment related environmental problems. K estimation methods are developed in many soil erosion and water quality models. These methods are developed for data rich areas that pose a challenge for areas with limited soils data. Unlike others, the required soil parameters to calculate K factor on the Erosion Productivity Impact Calculator (EPIC) model can be extracted from the Food and Agricultural Organization (FAO) world database. Hence, verifying the FAO soil database and developing an alternative soil erodibility method (KET) by mimicking the equation of K used in the EPIC model as the main goal, 203 soil samples were collected and used from different soil units of the Ethiopian Rift Valley Lake Basin (ERVLB) soils. Unlike the K of EPIC model, KET is developed based on the physical properties of a soil that can be easily measured in a laboratory. The similarity of results obtained using KET is compared with the results of the EPIC-K method by using model performance statistics. Statistically, the performance of KET is excellent and the soil analysis result of ERVLB deviates from the FAO soil database on lower altitude areas of the basin. When KET is projected for overall soil units of the country, it predicts 35.7% of the country soil with less than $\pm 5\%$ relative error. On average, the alternative erodibility equation (KET) can be applied to overall country soils with a relative error of -9.88% with a standard deviation of 6.4. By applying KET, the ERVLB, as well as the country K map, is produced. Hence, we recommend that the developed soil erodibility map developed for ERVLB can be confidently used since it is validated using field data.

Keywords: Soil erodibility (K); EPIC model; FAO soil database; Ethiopia; Rift Valley

² Alemu O. Aga, Assefa M. Melesse and Bayou Chane (2018). An Alternative Soil Erodibility (KET) Estimation Approach for Data Scarce Regions: A Case of Ethiopian Rift Valley Lake Basin.

5.1. Introduction

Erosion is a result of erosivity and erodibility. The potential ability of rain to cause erosion is called erosivity, whilst erodibility is defined as susceptibility/vulnerability of the soil to erosion (Defersha and Melesse, 2012). Soil erodibility is an important index to measure soil susceptibility to water erosion, and an essential parameter needed for soil erosion prediction models, such as the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and also in more complex sediment prediction models e.g. Soil Water Assessment Tool (SWAT) (Grey et al., 2014; Juliana and Melesse, 2015; Setegn et al., 2010), Agricultural Non-Point Source Pollution Model (ANGPS) (Melesse et al., 2011), and Erosion Productivity Impact Calculator (EPIC) (Auerswald et al., 2014). Practically it can be obtained directly from a standard plot or indirectly from empirical models.

The direct measurement of the soil erodibility in the field is considered as the most reliable way of estimation (Römkens et al., 1977). But such method requires the establishment and maintenance of natural runoff plots over lengthy and, expensive observation periods at various locations. Hence, it is a costly and time-consuming technique. To overcome this, numerous attempts have been made to simplify the technique and to establish estimators for soil erodibility calculation from readily available soil property data and standard (Römkens et al., 1997; Wischmeier et al., 1971). To date, the available soil erodibility calculation models, such as USLE (Wischmeier et al., 1971; Wischmeier and Smith, 1978), the Revised Universal Soil Loss Equation (RUSLE) (Römkens et al., 1988), the Erosion Productivity Impact Calculator (EPIC) (Sharply and Williams, 1990) and the Geometric Mean Diameter based (D_g) model (Renard et al., 1997) have been widely used around the world.

The K factor was originally derived from five variables; namely, the percentage of silt and very fine sand fraction, percentage of sand fraction, amount of organic matter, soil aggregation and soil permeability index that have to be combined in a K factor nomograph factor nomograph (Wischmeier et al., 1971). Later, a sixth variable, namely rock fragment cover, was added by Wischmeier and Smith (1978), who also provided the classical K factor equation to allow calculation of the K factor. Since the amount of data required by original developed model (Wischmeier et al., 1971; Wischmeier and Smith, 1978) is large, Sharply and Williams (1990) have derived an alternative erodibility estimation method by using only two soil properties: soil organic carbon content and soil particle size distribution. Furthermore, for soils, the measured soil erodibility factor from which the K-value can be derived from measured soil properties are unavailable, Renard et al. (1997) derived an alternate, yet less accurate, expression for estimating K-values using only soil parameter: Geometric Mean Diameter of the soil particles (Wang et al., 2016).

Numerous researchers have attempted to determine alternative erodibility estimation models for specific regions or conditions (watershed/county-scale studies) based on original models (Auerswald et al., 2014; Walker, 2017). Similarly, researchers have attempted to determine which model is the best-suited to soil erodibility estimation at various scales (Römken et al., 1977; Torri et al., 1997) and several efforts have been made to compare models for specific regions or conditions (e.g., watershed/county-scale studies or rainfall simulation studies) (Hussein et al., 2007; Wang et al., 2012, 2013; Zhang et al., 2004, 2008). For example, Wang et al. (2016) have improved USLE-K factor prediction for China's soil and developed an alternative soil erodibility estimation model by using soil organic matter and geometric mean diameter of the soil particles. In different regions, Anache et al. (2016); Wang et al. (2012);

Wawer et al. (2005) and Zhang et al. (2008) tested USLE-K, EPIC and Dg models for specific areas and developed an alternative K method by using an easily accessible soil parameters by applying a non-linear regression fitting technique.

However, in developing countries, the adaptation of the research results of the investigations to other places still remains a big challenge due to the insufficient input data to make necessary adjustments for the specific situations of the area under consideration (Geleta, 2011). For example, in Ethiopia, very few investigations have been done so far for the specific situation of soils of the country. One of the most used soil erodibility factors (K) in Ethiopia is that recommended by Hurni (1985) and Helldén (1987), a method for the rough estimation of K factor based on soil colour, which is still used today (Ayalew, 2015; Gashaw et al., 2017; Gelagay and Minale, 2016; Miheretu and Yimer, 2018; Tadesse et al., 2017).

For an accurate prediction of K values, it requires to have detail key soil inherent properties like texture, organic matter, structure and permeability. Hence, estimating based only on colour may have been subjective. This limited availability of an appropriate method for the estimation of soil erodibility factor is the main bottleneck for prediction of a reliable sediment yield in the country (Geleta, 2011). MOWR (2009) is using the method developed by Sharply and Williams (1990) for EPIC model to determine the K factor of the western Lake Ziway sub-basin to estimate the basin's sediment rate. In fact, from various soil erodibility prediction methods (R/USLE-K and Dg models), Sharply and Williams (1990) equation developed for EPIC model is applicable for data limited area (Geleta, 2011; Zhang et al., 2008) and the required soil parameters can be easily extracted from FAO world soil databases. Similarly, an investigation conducted by Anache et al. (2016); Wang et al. (2012); Wawer et al. (2005) and

Zhang et al. (2008) confirms that the soil erodibility estimation method developed in EPIC model is predicting better than others.

The soil erodibility estimation method developed in EPIC model requires soil texture class and its organic carbon contents (OCC). Practically, determining of soil chemical parameter is more complex than physical parameters (Geleta, 2011). The OCC of a soil is mostly determined by burning the soil samples which accuracy is always under question for non-well-developed laboratories (Geleta, 2011). And in similar manner, to use the FAO world soil database, its reliability should be verified with major soils class. Therefore, the main objective of this chapter are: (1) to verify the reliability of the FAO world soil database for the study area; (2) to derive an alternative soil erodibility estimation approach with a more simplified input parameter to predict the soil loss by empirical or semi distributed models by mimicking the original K values developed for EPIC model; and (3) to provide a regional soil erodibility map for water erosion areas in Ethiopia Rift valley lake basin using an alternative K-factor prediction approach.

5.2. Study area description

The Ethiopian Rift Valley Lakes Basin (Figure 5.1) is situated in the southern part of the country and characterized by a chain of lakes. It stretches from the northeast to the southwest just north of Lake Ziway via Lakes Abiyata, Langano, Shala, Hawassa, Abaya, Chamo and Chew Bahir up to the border with Kenya. The basin has a total area of 53,000 km² and geographically, it extends from 8°30'N to 4°25'N latitude and 36°30'E to 39°30'E longitude.

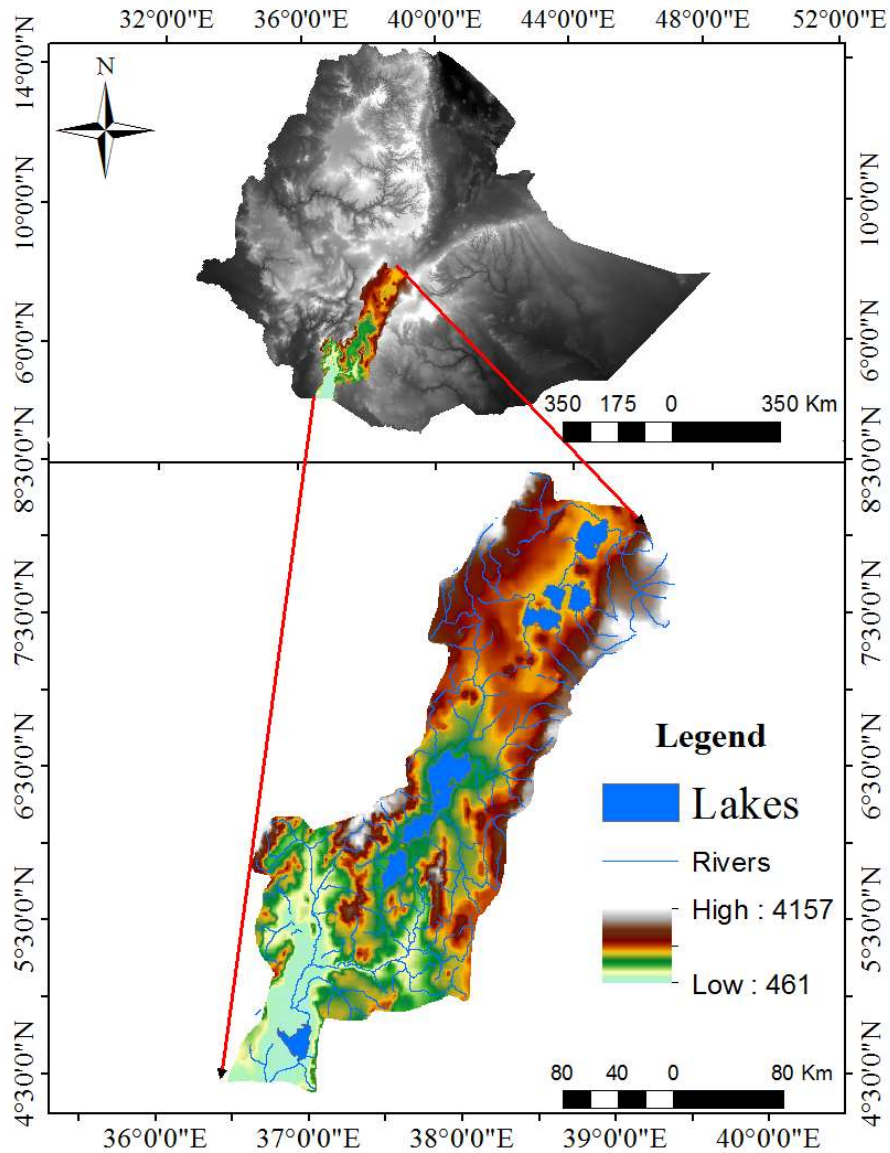


Figure 5.1 Location of Ethiopian Rift Valley Lake Basin

The geology of the rift valley lakes basin is divided into four major groups of rock: Mesozoic sedimentary rock, Oligocene to middle Miocene pre-rift volcanic rock and middle-Miocene to Holocene syn-and post- rift volcanic rocks and unconsolidated sediments (MOWR, 2010). The vegetation of the northern part of the central valley is a mixture of open bush, open woodland and moderately to intensively cultivated land. East of Lake Ziway, the Wonji Fault Belt consists of open and dense bush land up to the Asella plain, where intensive cultivation and

open grassland rises to open woodland and grassland at the boundary. The central plain around Lakes Shala, Langano and Abiyata is characterised by open woodland and wooded grassland with intensive cultivation to the south and west. Between Lake Hawassa and Abaya, where the valley narrows, the central part is characterised by open and dense bushland with some erosion (Figure 5. 2).

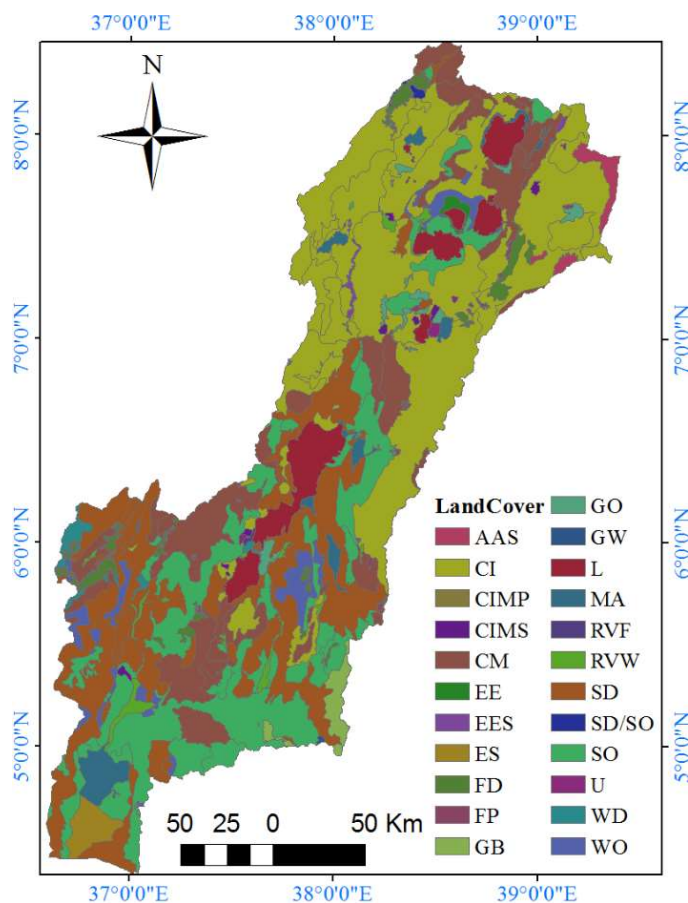


Figure 5 2 Land use types of the study area

Where U--Urban, CIMS-- Intensive Mechanised Cultivation State, CIMP---Intensive Mechanised Cultivation Private, CI -- Intensive Smallholder Cultivation, CM--Moderate Smallholder Cultivation, AAS --Afro-alpine shrubland, FD--Disturbed High Forest, FP -- Plantation Forests, WD--Dense Woodland, WO --Open Woodland, RVF--Riparian Forest, RVW--Riparian Woodland, SD--Dense Shrubland, SO -- Open Shrubland, GO -- Open Grassland, GB -- Bushy Grassland, GW--Wooded Grassland, MA--Marshland, ES --Salt Flat, EE --Bare Soil, EES ---Bare soil with scattered vegetation and L --Lake Water.

The major soil groups identified in the reconnaissance soil survey of Rift Valley Lakes Basin (MOWR, 2010) are: Luvisols, Cambisols, Nitisols, Vertisols, Solonchaks, Arenosols, Andosols, Fluvisol and Leptosols. The soil map of Ethiopian Rift Valley Lake Basin is given in Figure 5.3.

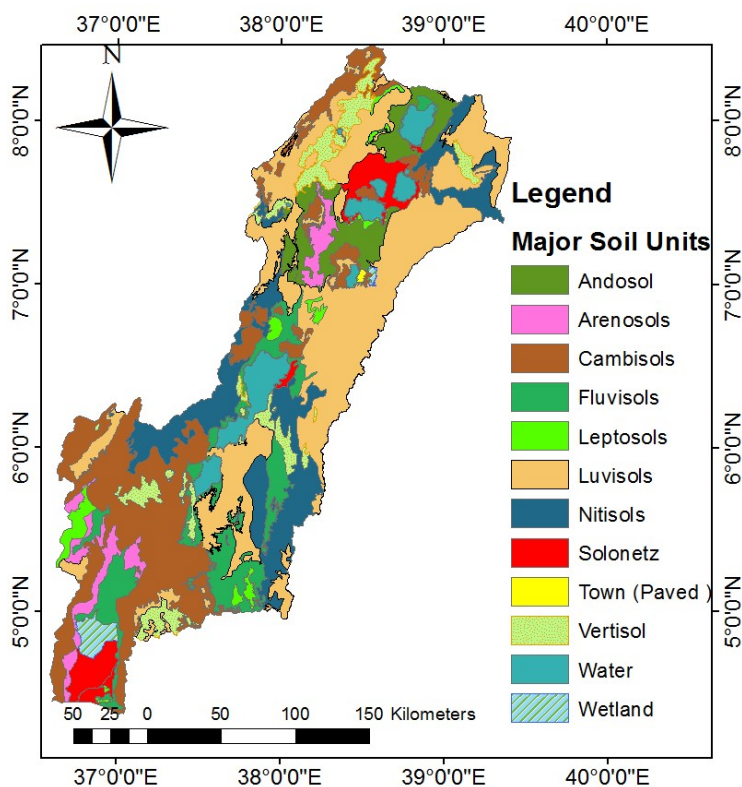


Figure 5 3 Soil map of Ethiopian Rift Valley Lake Basin

5.3. Methodology

5.3.1. Soil erodibility (*K*) estimation methods

One of the oldest soil erodibility estimation method was originally derived by Wischmeier et al.(1971). Next, Renard et al. (1997); Sharply and Williams (1990); Wischmeier and Smith (1978) proposed formulas for soil erodibility estimation with specific soil properties and to date, are widely used around the world.

The selection of these erodibility equations depends on the availability of input data for the specific area under consideration. The [Wischmeier and Smith \(1978\)](#) equation can be applied to areas where there is a complete soil profile parameters like soil texture, soil organic matter content (OM), soil structure classes and soil permeability. An algebraic expression derived by [Wischmeier and Smith \(1978\)](#) to calculate k factor for the soil with silt fraction does not exceed 70% is:

$$K = \frac{[0.00021 * M^{1.14} (12 - OM) + 3.25 (S - 2) + 2.5 (P - 3)]}{100} \quad (5.1)$$

where K is the soil erodibility factor, M is the product of percent of silt +very fine sand and the percent of all soil fractions other than clay, OM is soil organic matter content (%), S is the soil structure code used in soil classification and P is the soil permeability class.

Like as, the equation derived by [Sharply and Williams \(1990\)](#) can be applied in areas where there are sufficient data sets related to soil particle size distribution and soil organic carbon content. The [Sharply and Williams \(1990\)](#) soil erodibility index values have been calculated as the following equation that put as EPIC (Erosion productivity impact calculator):

$$K = \left\{ 0.2 + 0.3 \exp \left[-0.0256 SAN \left(1 - \frac{SIL}{100} \right) \right] \right\} * \left(\frac{SIL}{CLA + SIL} \right)^{0.3} \\ * \left(1 - \frac{0.25C}{C + \exp(3.72 - 2.95C)} \right) * \left(1 - \frac{0.7SN1}{SN1 + \exp(-5.51 + 22.9SN1)} \right) \quad (5.2)$$

where SAN, SIL and CLA are sand fraction (%), silt fraction (%), clay fraction (%), respectively. C is the soil organic carbon content (%) and SN1 equal to 1- SAN/100. This equation results in a K-factor with units of ton acre hour hundreds of acre⁻¹ foot⁻¹* tonf⁻¹ inch⁻¹ and to convert in to SI unit (t ha hr/ha MJ mm), will be multiply by 0.1317 ([Foster et al., 1981](#); [Renard et al., 1997](#)).

Similarly, the applicability of [Renard et al. \(1997\)](#) equation depends on the availability of data pertaining to the calculation of the geometric grain size. [Renard et al. \(1997\)](#) developed an empirical equation based on a natural plot and simulated rainfall data derived from global data. The erodibility equation was related to the geometric mean diameter (Dg) of soil particle and is equated as:

$$K = 7.594 \left\{ 0.0017 + 0.0494 \exp \left[-\frac{1}{2} \left(\frac{\text{Log}(Dg) + 1.675}{0.6986} \right) \right]^2 \right\} \quad (5.3)$$

where Dg is geometric mean diameter of soil particle and determined as Equation 5.4.

$$Dg = \text{Exp} (0.01 * \sum_{i=1}^n (f_i * \ln m_i)) \quad (5.4)$$

where f_i is the weight percentage of primary particle size fraction in percent and m_i is the arithmetic mean of the particle size (mm) and n is the number of particle size fractions.

Based to the data requirement, estimation methods developed by [Wischmeier and Smith \(1978\)](#) requires large amount of soil properties data than method developed by [Sharply and Williams \(1990\)](#) and the method of [Sharply and Williams \(1990\)](#) also requires relatively large data than [Renard et al.\(1997\)](#). Practically determining of large soil parameter from soil map is difficult and when more parameters are considered more error will happen during data collection and analysis ([Geleta, 2011](#)). Next to number of data, the sensitivity of a parameters used is also one of the factor for accurate estimation of the methods. For example, in equation K-Dg model, the only parameter used to predicate the K value is geometric mean diameter (Dg) of the particle. This geometric grain size which is a function of the particle size fraction and particle size limit is too sensitive to small discrepancies as it is represented by an exponential function ([Geleta, 2011](#)) (see Equation 5.3). The small discrepancies in the data of

particle size fraction and particle size limit can lead to large errors. To avoid such discrepancies a detailed investigation of the particle size information is required which needs many representative soil sample data and accurate laboratory analysis. Hence, this is also difficult to apply for region who has no access to use accurate laboratory analysis where and when needed. This is true for most developing country like Ethiopia. In most developing country researchers are using erodibility estimation method developed by [Sharply and Williams \(1990\)](#) (EPIC-K). The advantage of using [Sharply and Williams \(1990\)](#) (EPIC-K) method is its low number of data requirement. And, another advantage of the erodibility equation of EPIC-K is that its input requirements can be extracted easily from the Food and Agricultural Organization (FAO) world soil database.

Moreover, the demand for a great number of soil input parameters remains a major challenge for estimating erodibility factor. Minimizing the input requirement for the soil erodibility factor estimation can alleviate the difficulty of obtaining sufficient data ([Geleta, 2011](#)). Therefore, the method developed by [Sharply and Williams \(1990\)](#) (EPIC-K) is selected to develop an alternative soil erodibility estimation method in mimicking the original K.

5.3.2. Dataset

The soil map of the Ethiopian Rift Valley Lake Basin and the country is available from the Ethiopian Ministry of Water, Irrigation and Electricity (MoWIE). To compute the soil erodibility by EPIC- K method, complete data sets related to soil texture and soil organic carbon content should be available. Hence, the physical and chemical properties of the soils for Ethiopia Rift Valley Lake basin have been collected from the field and MoWIE. In the master plan study of the Ethiopian Rift Valley Lake Basin (ERVLB), the soil sample was

collected and analysed from major soil types of the basin and the sampled points are shown in Figure 5.4.

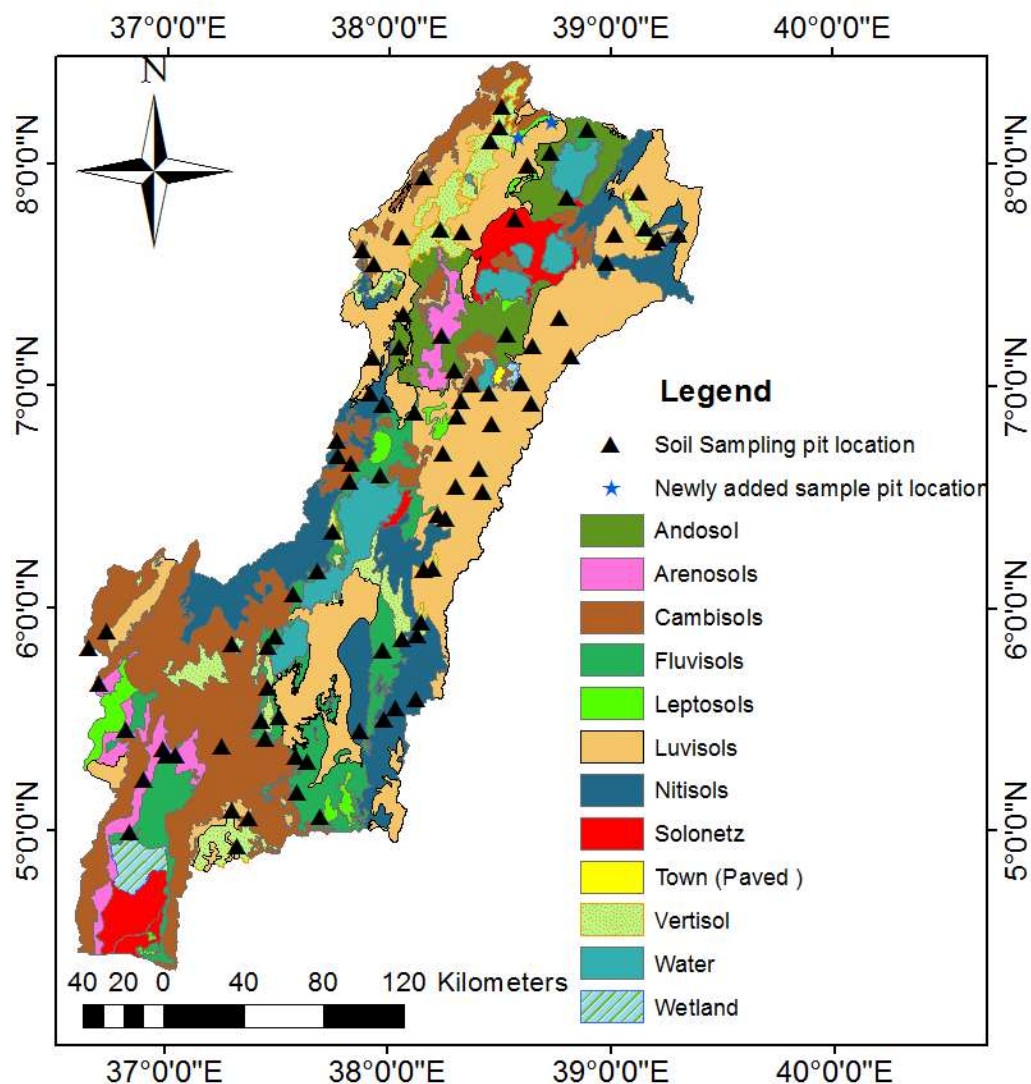


Figure 5 4 Soil sampled locations of Ethiopian Rift Valley Lake Basin

As shown in Figure 5.4, no soil sample tests were taken from the Leptosol-dominated locations of the basin. In the basin, Leptosol covers around 206,611.42 ha (3.9% total basin). Hence, additional soil tests were done in this study to investigate the physical properties of those soils. To do so, soil samples have been collected from two Leptosol-dominated parts of

the basin (Figure 5.4). The soil samples were collected from 70 cm × 70 cm pit with a depth of 150 cm. The sampling has been done separately at three depth profiles: the first from the depth of 0 to 50 cm, the second from 50 to 100 cm and the third from 100 to 150 cm. To analyse the bulk density of the soil, undisturbed core samples were taken from each pit.

To test its physical parameters, the particle size analysis was performed using the hydrometer method by following laboratory guideline procedures recommended by [Milford \(1997\)](#). Similarly, the bulk density of the soils was calculated from its 24 h oven-dry weights.

5.3.3. Developing an alternative approach (KET) to estimate soil erodibility rates of ERVLB

The mathematical expression of KET is developed based on natural phenomena of soil erosion on different soil class. Naturally, soils with a high content of silt tend to have high erodibility and erodibility is low for clay rich soils. Clay particles mass together into larger aggregates that resist detachment and transportation. Soils containing large proportions of sand have relatively large pores through which water can drain freely. These soils are at less risk of producing runoff. Similarly, soil bulk density is dependent on soil texture and soil organic matter contents. As reported by [Jepsen et al. \(1997\)](#), soil erosion decreases with increases in bulk density.

Hence, to develop an alternative soil erodibility (KET) estimation model for the basin, we considered the relation of K with texture and BD as K is directly proportional to percent silt but inversely proportional to clay and sand contents as well as bulk density. From this inverse and direct proportionality of soil parameters, an algebraic expression for K is developed as:

$$K \propto \left(\frac{\% \text{ Silt}}{\% \text{ Sand} + \% \text{ Clay}} \right) * \frac{1}{BD} \quad (5.5)$$

To investigate the developed algebraic expressions with an original K value, the basins K values were calculated by using K factor developed for EPIC model by [Sharply and Williams \(1990\)](#) and the ratio of major soil texture and its BD is compared statistically (Table 5.1).

Table 5. 1 Pearson Correlations for ratio of soil parameters and calculated K values

Ration of Soil Physical Parameters	Pearson Correlations
$\left(\frac{\% \text{ Silt}}{\% \text{ Sand}} \right)$	0.756**
$\left(\frac{\% \text{ Silt}}{\% \text{ Sand} + \% \text{ Clay}} \right)$	0.921**
$\left(\frac{\% \text{ Silt}}{\% \text{ Sand} + \% \text{ Clay}} \right) * \frac{1}{BD}$	0.941**

** Correlation is significant at the 0.01 level (2-tailed). BD is Bulk density (g.cm^{-3}).

As shown in Table 5.1, for both cases, the ratio of silt to sand and clay with ratio of BD reflect the highest correlation than using only the textural class. Hence, the alternative soil erodibility estimation method is formulated as the ratio of silt to total sand and clay with ratio of bulk density. By considering the percentage of silt to sand and clay with ratio of bulk density as an explanatory variable and the K values calculated by [Sharply and Williams \(1990\)](#) in EPIC-K method as a dependent variable, a nonlinear regression equation has been established as (Equation 5.6)

$$KET = \beta \left[\left(\frac{\% \text{ Silt}}{\% \text{ Sand} + \% \text{ Clay}} \right) * \frac{1}{BD} \right]^\alpha \quad (5.6)$$

where: KET = Newly proposed alternative soil erodibility factor (t Acre Hour Hundreds acre⁻¹foot⁻¹ tonf⁻¹inch⁻¹), % Silt, % Sand and % Clay is percentage of silt, sand and clay proportion in the soil respectively, BD = Bulk density of the soil (g.cm⁻³), β and α are coefficients determined through a regression and optimization procedure.

5.3.4. Model evaluation and statistical analyses

The newly derived model has been evaluated and tested statistically by using coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), root mean square error (RMSE) observations standard deviation ratio (RSR) and Percent bias (PBIAS).

The Coefficient of determination (R^2) describe the degree of correlation between the result calculated from KET and EPIC-K. A R^2 value close to one indicates a better performance. However, it is very sensitive to extremely high values. The Nash–Sutcliffe efficiency (NSE) is one of the most commonly used criteria. NSE is a normalized statistic that determines the relative magnitude of the residual variance as compared from the two models. NSE ranges from $-\infty$ to 1 and typically values greater than 0.5 is considered an acceptable limit ([Moriasi et al., 2007](#)). For NSE, the squared difference in equation becomes the limitation (overestimating higher values and neglecting lower values). The RMSE (root mean square error)-observations standard deviation ratio (RSR) combines the feature of an error index RMSE and a normalization factor so that it can be applied to various constituents. RSR ranges from 0 to ∞ and value close to zero indicates higher accuracy of the model performance.

Percent bias (PBIAS) measures the average tendency of the predicated result by KET to be larger or smaller than EPIC-K. The optimal value of PBIAS is 0.0, with low-magnitude values

indicating accurate model simulation. Positive values indicate model underestimation bias and negative values indicate model overestimation bias.

To verify the applicability of the newly developed alternative soil erodibility model for overall soils of Ethiopia, the digital soil map of Ethiopia (Figure 5.3) was obtained from MOWIE and its input requirements were extracted from the [FAO \(1998\)](#) soil database.

5.4. Results and discussion

5.4.1. Applicability of FAO world soil database for the study area

Using data from 90 pits, 203 soil samples were used to evaluate the applicability of FAO world soil map and to generate an alternative soil erodibility estimation model. The similarity and variation of the soil fractions measured in the field have been compared between the [FAO \(1998\)](#) soil database properties (Figure 5.5).

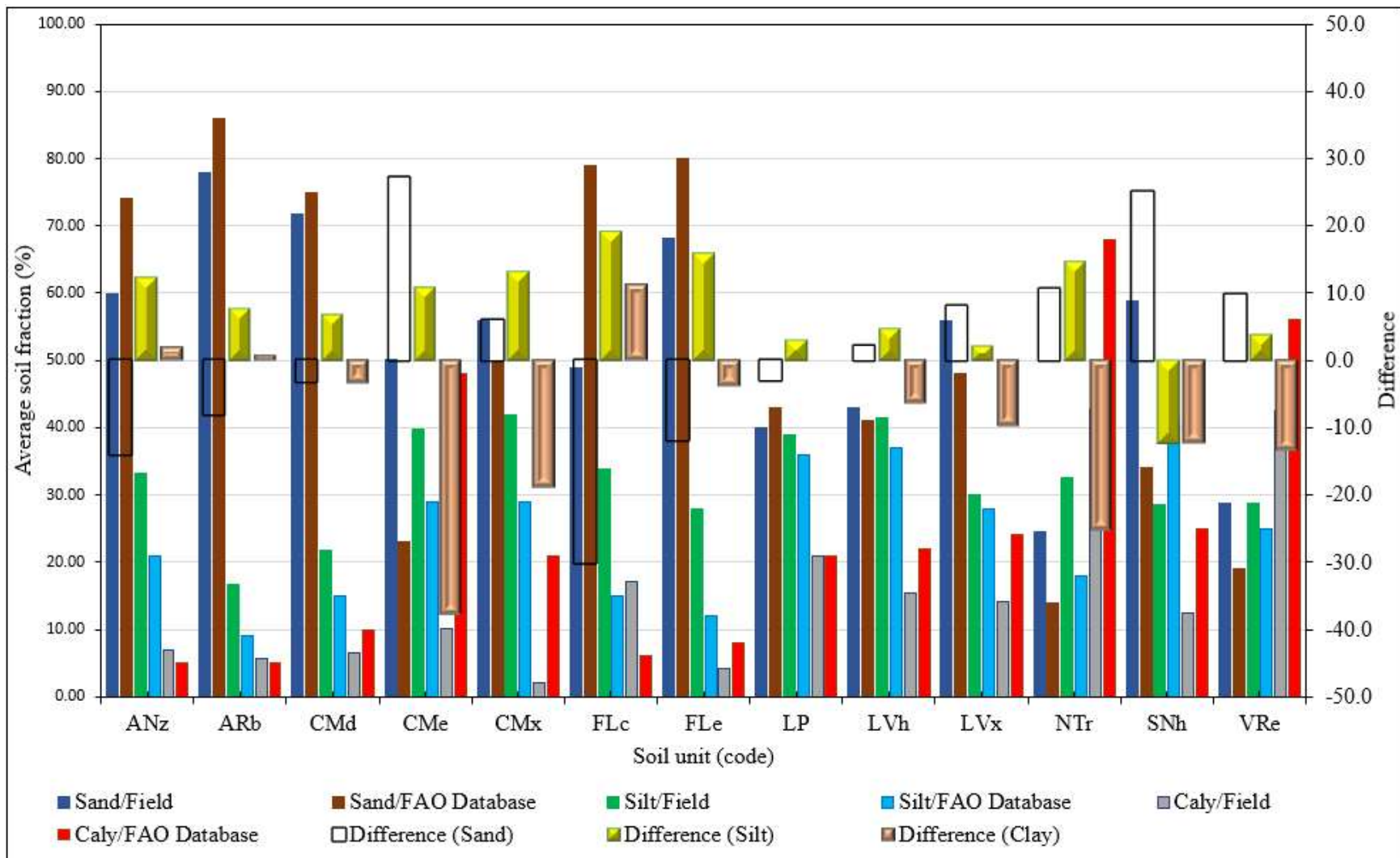


Figure 5 5 Comparison of field measured soil property with of FAO soil database properties

Where: ANz is Vitric Andosols, Arb is Cambic Arenosols, CMd is Dystric Cambisols, CMe is Eutric Cambisols, CMx is Chromic Cambisols, FLc is Calcaric Fluvisol, FLe is Eutric Fluvisols, LP is Leptosols, LVh is Haplic Luvisols, LVx is Chromic Luvisols, NTr is Rhodic Nitisols, SCh is Haplic Solonchaks and VRe is Eutric Vertisols

As shown in Figure 5.5, for Vitric Andosol (ANz), Eutric Cambisol (Cme), Fluvisol (FL) and Haplic Solonetz (SNh), there is significant variation in soil texture classes. As shown in Figure 5.3, within the basin, Vitric and Fluvisol are found on depressions, alluvial plains, lacustrine plains adjacent to lakes, main streams, river meander belts of major rivers and in areas subject to annual flooding and consequently receiving fresh sediments from each flood. Hence, for these two-soil classes, the sand proportion is decreased and the silt and clay fraction has increased. Similarly, both Cambisol and Solonetz soil is also located on low lying areas of the basins and the fraction of sand is significantly greater than the FAO database. In the low-lying areas, there is a chance of deposition of sand if the upper catchment is dominated by sandy soils. Generally, soils located in the lower sections of the basin showed a deviation from the FAO soil database which may be due to eroded soil deposition. In order to improve this, the sample should be taken from deeper depths to analyse samples from the different soil horizons.

5.4.2. An alternative equation to determining soil erodibility values

By mimicking the original K developed for EPIC model, an alternative soil erodibility model (KET) for Ethiopia Rift Valley Lake basin is developed as:

$$KET = 0.34 \left[\left(\frac{\% \text{ Silt}}{\% \text{ Sand} + \% \text{ Clay}} \right) * \frac{1}{BD} \right]^{0.33} * 0.1317 \quad (5.7)$$

where: K_{ET} is the newly proposed alternative soil erodibility factor (t ha hr/ha MJ mm) and BD is bulk density of the soil (g.cm^{-3}).

The soil erodibility factor using the newly developed K method (KET) and EPIC -K method is shown in Figure 5.6.

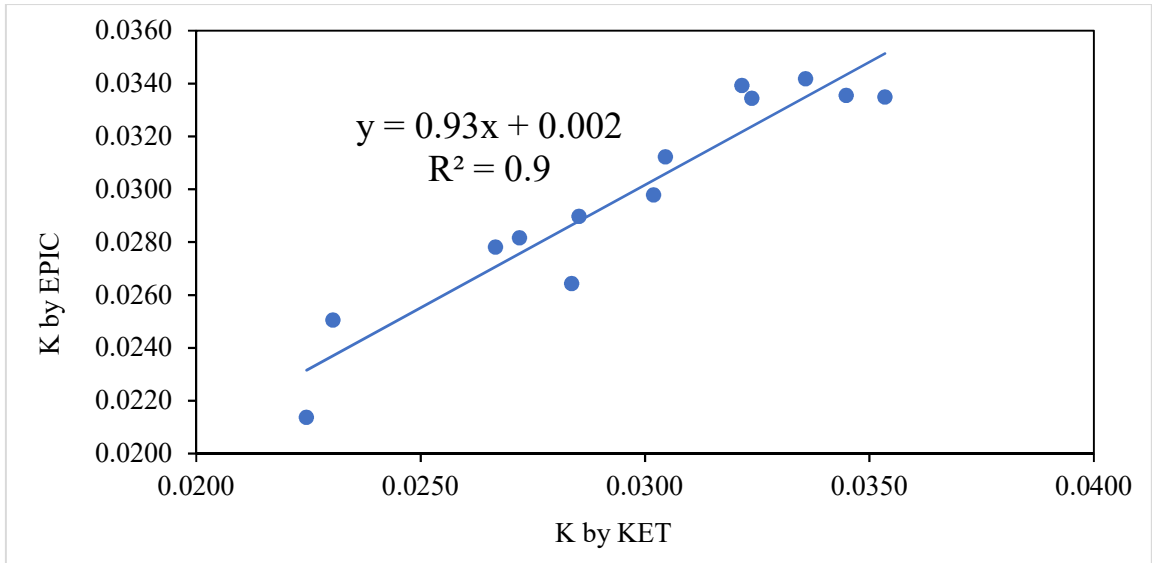


Figure 5.6 Soil erodibility value determined by KET and EPIC-K method

As [Moriassi et al. \(2007\)](#) demonstrated, if the R^2 Value is > 0.9 , 0.9 to 0.75 , 0.65 to 0.75 and > 0.50 , the model can be rated as; excellent, very good, adequate and satisfactory performance, respectively. From Figure 5.6, it can be observed that the alternative soil erodibility model (KET) performance is excellent. Additional numerical criteria of model performance evaluators namely: NSE, RSR, RRMSE and PBIAS are determined and summarized in Table 5.2.

Table 5.2 Statistics values for model performance

Statistics	R^2	NSE	RSR	RRMSE	PBIAS
Statistics values	0.9	0.9	0.31	0.024	-0.64

As recommended by [Moriassi et al. \(2007\)](#), the high R^2 and NSE (above 0.9) values and the reasonably low RSR (below 0.5) and PBIAS (below 5) indicate the excellent correlation and agreement between developed alternative soil erodibility estimation (KET) method and EPIC

method. Furthermore, the applicability of KET is tested by comparing the value of soil erodibility estimated by using both methods: KET and EPIC (Figure 5.7).

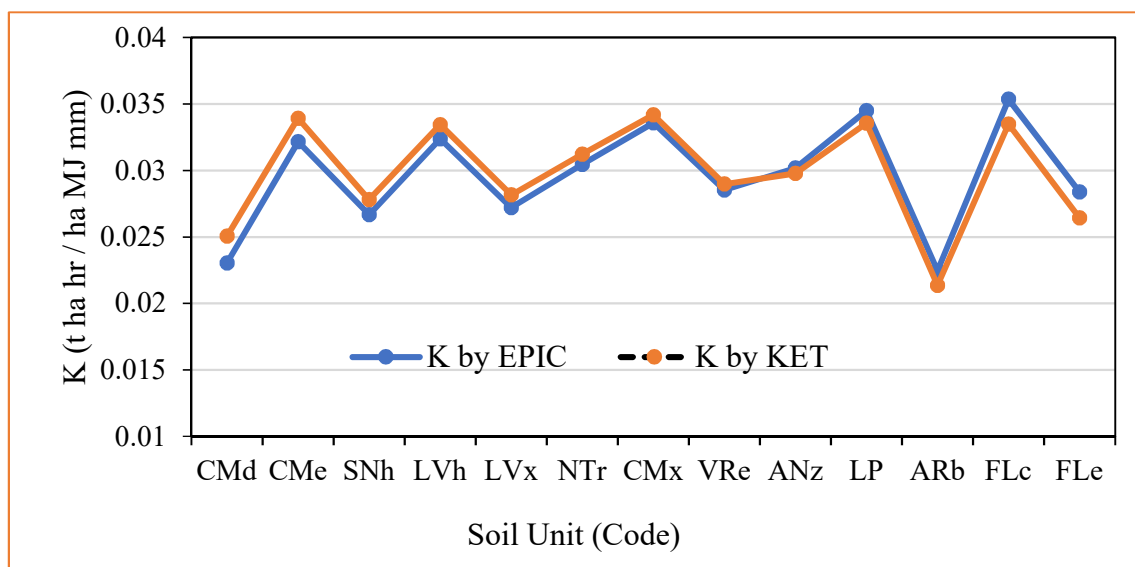


Figure 5.7 Comparison of soil erodibility factors estimated by EPIC-K and KET for ERVLB soils

In Figure 5.7, soil erodibility factor calculated by KET almost replicated the entire trend of value predicted by EPIC. Similarly, in Table 5.2, the statistical analysis result indicated as an alternative erodibility estimation equation (KET) can represent EPIC-K equation for ERVLB soils. It is shown that both KET and EPIC-K approaches are good in replicating measured soil erodibility and can be concluded that the newly developed alternative soil erodibility method can be used in ERVLB. The Soil erodibility map of ERVLB by KET and EPIC-K method is given in Figure 5.8.

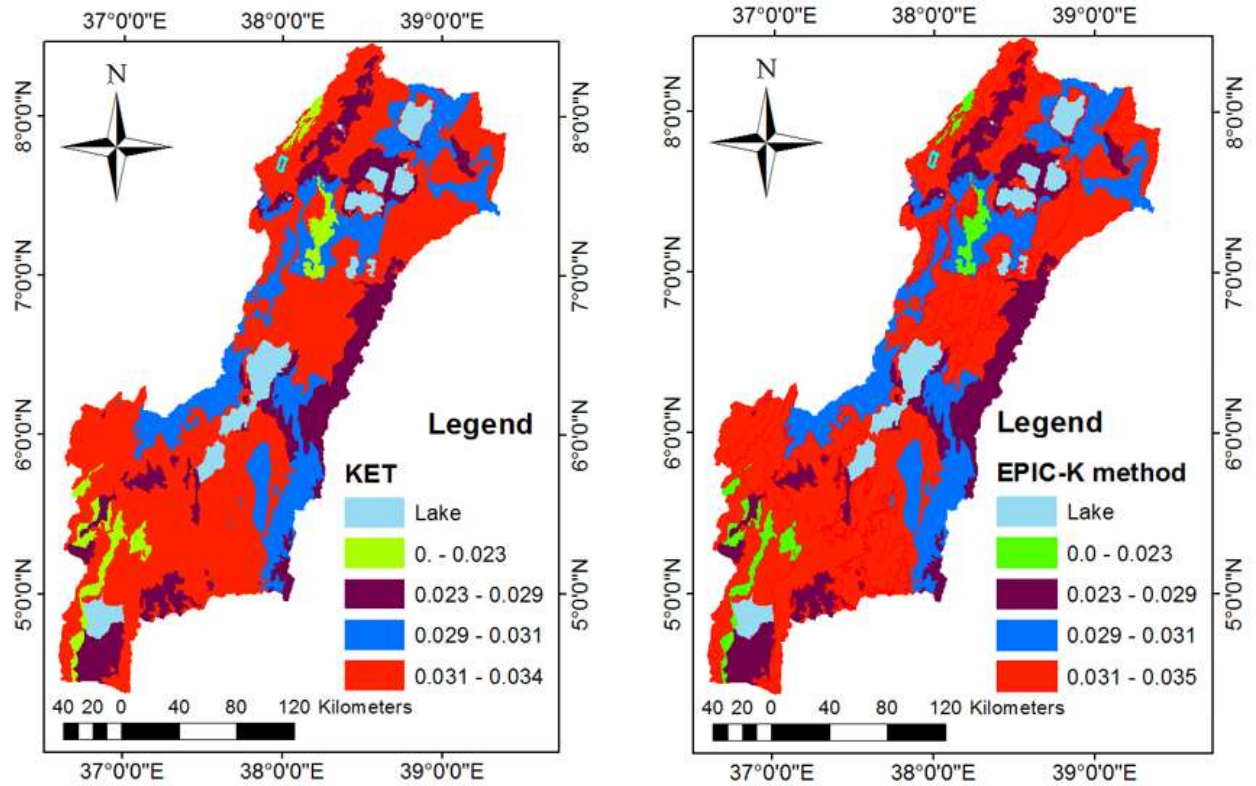


Figure 5.8 The Soil erodibility map of ERVLB. The left by KET and the right by EPIC-K

5.4.3. Evaluation of alternative soil erodibility estimation method (KET) for soils of Ethiopia

Even though the goal of the study is to develop K factor for Ethiopian Rift Valley Lake Basin, its applicability was tested for all soils of the country. Ethiopian soil map indicates the existence of 56 different soil units in the country. Hence, the required soil parameters were extracted from FAO world soil database. For evaluations, the 13 soil units (type) that were used to establish the KET equation were excluded. Hence a total of 43 soil types have been considered in analysis and the newly proposed soil erodibility estimation model was applied to calculate the soil erodibility values of each soil type and compared with the erodibility factors calculated by EPIC-K method.

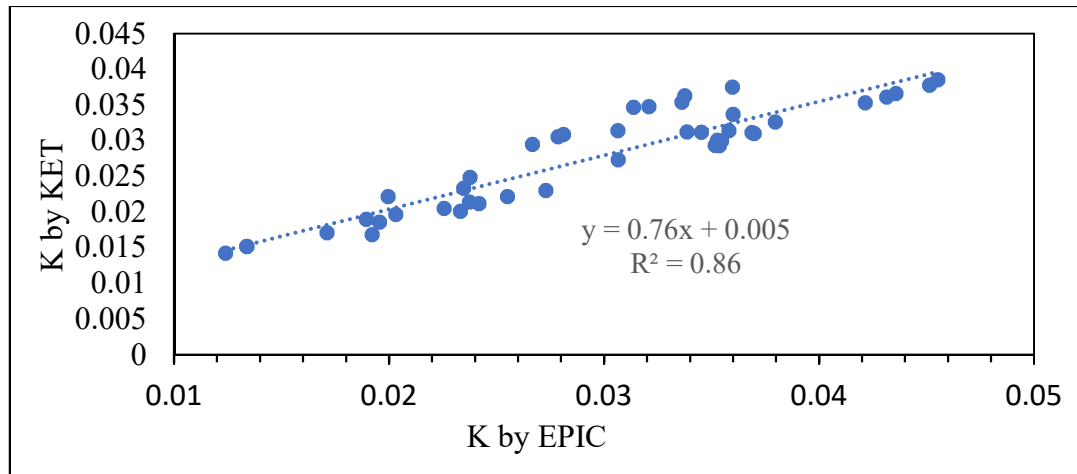


Figure 5.9 Soil erodibility value determined by KET and Sharply and Williams (EPIC-K) method

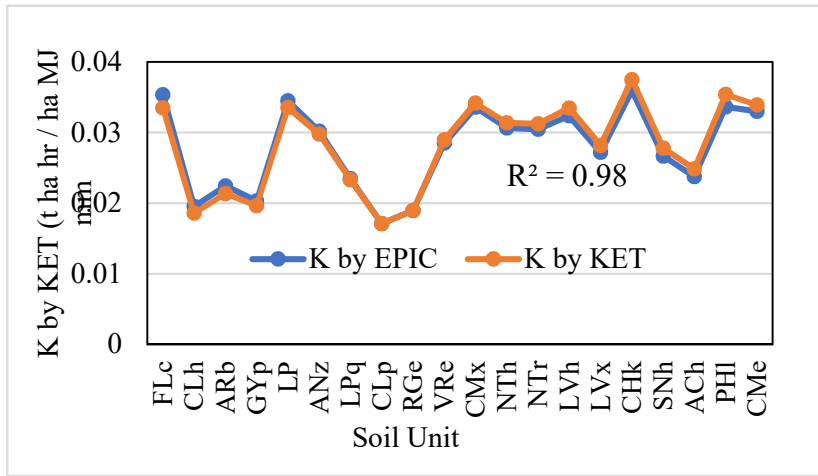
For the total of 43 Ethiopian soils, the statistical correlation of erodibility factor determined by using newly developed K model (KET) and EPIC-K method is given in Figure 5.9. Model performance using NSE, RSR and PBIAS is summarized in Table 5.3.

Table 5.3 Statistics values for model performance

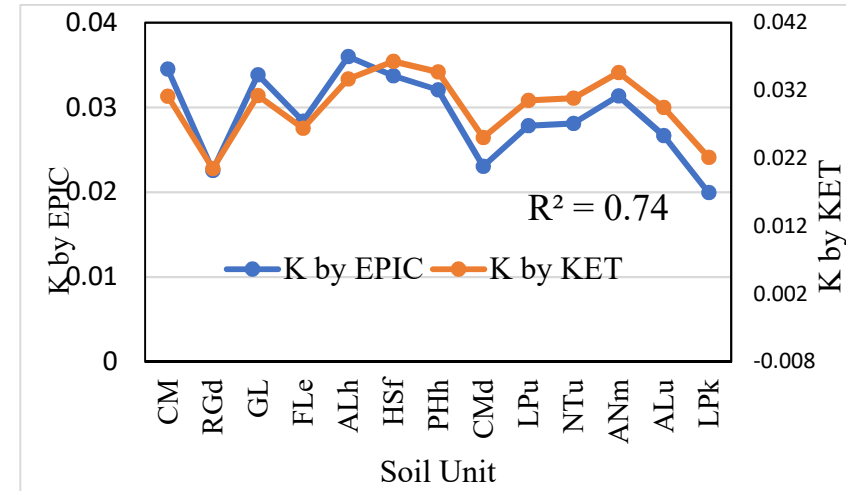
Statistics	R ²	NSE	RSR	PBIAS
Statistics values	86	0.8	0.45	6.64

According to statistical model performance result (Table 5.3), the developed alternative soil erodibility equation (KET) performance is excellent for RSR and very good for coefficient of determination (R²), PBIAS and NSE (Moriassi et al., 2007). Statistically, the alternative erodibility estimation method (KET) is appropriate to use for overall soil units of the county. But the calculated Percent bias (PBIAS) is positive and which indicates the KET is underestimating the real erodibility value. To identify the group of soil which have high relative error between the two methods, their relative error was calculated. Based on the

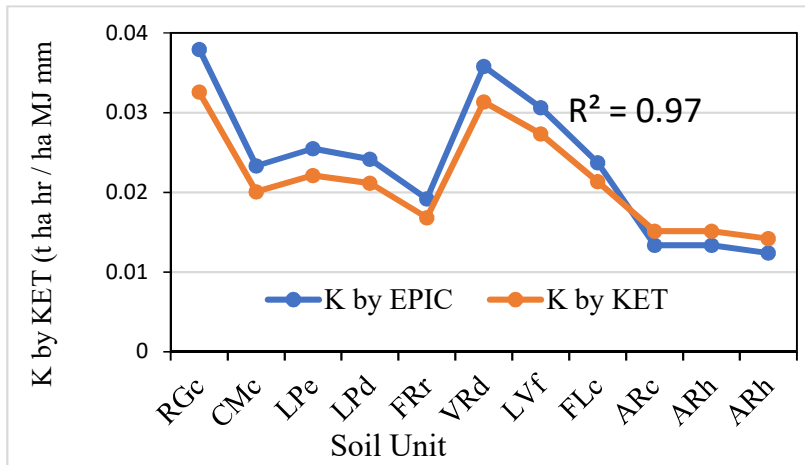
magnitude of their relative error, the soils of Ethiopia is classified into four groups. Group one: soils which show relative error less $\pm 5\%$, group two, three and four are soil which have relative errors less than ± 10 , -15 and -20% , respectively.



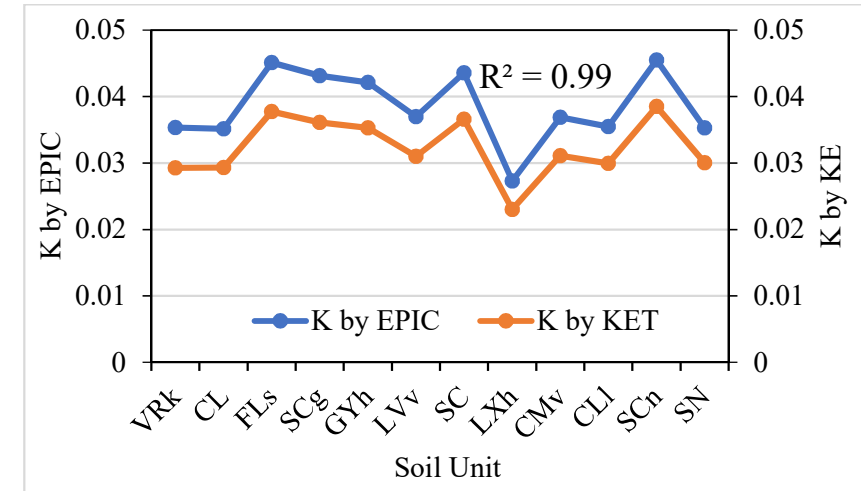
A. Group one: Soil with relative error less than $\pm 5\%$



B. Group Two: Soil with relative error less than $\pm 10\%$



C. Group three: Soil with relative error less than -15%



D. Group Four: Soil with relative error less than -20%

Figure 5 10 Comparison of soil erodibility factors estimated by the equation of EPIC-K (Sharply and Williams, 1990) and KET for

Ethiopia soil

As shown in Figure 5.10, the alternative erodibility model predicted 35.7 % of the country soil with an error of $\pm 5\%$ (35.7%, $\pm 5\%$). Similarly, (23.21%, ± 6 to $\pm 10\%$), (19.6%, -11 to -15%) and (21.4%, -16 to -20) were also found. On average, the alternative erodibility equation (KET) can be applied for more than 58.9 % of the country soil with an average error of $\pm 5.3\%$ and standard deviation of 3.2. The erodibility factor for the 41.1% of the country soils were predicted with an error of $\pm 13.31\%$ and standard deviation of 10.3. Overall, the newly developed soil erodibility factor has a relative error of -9.88% with standard deviation of 6.4 for the national soils.

The result obtained in this study may reflect the country's soil erodibility rate. On most erodibility studies, the existing soil erodibility models are over estimating the result when compared with field measured data. For example in China, [Wang et al. \(2013\)](#) reported as the EPIC model is overestimating soil erodibility by 51.1% on purple soil region and 18.5% in black soil regions of China. [Wang et al.\(2012\)](#); [Wawer et al. \(2005\)](#) and [Zhang et al. \(2008\)](#) evaluated the performance of different soil erodibility models and reported almost similar results with [Wang et al. \(2013\)](#). Therefore, in conclusion, the prediction error obtained from KET is within acceptable range. Hence, to improve its overall performance, it is advisable to check observed data from natural runoff plots. Based on the developed alternative erodibility equation, the soil erodibility map of country was developed (Figure 5.11).

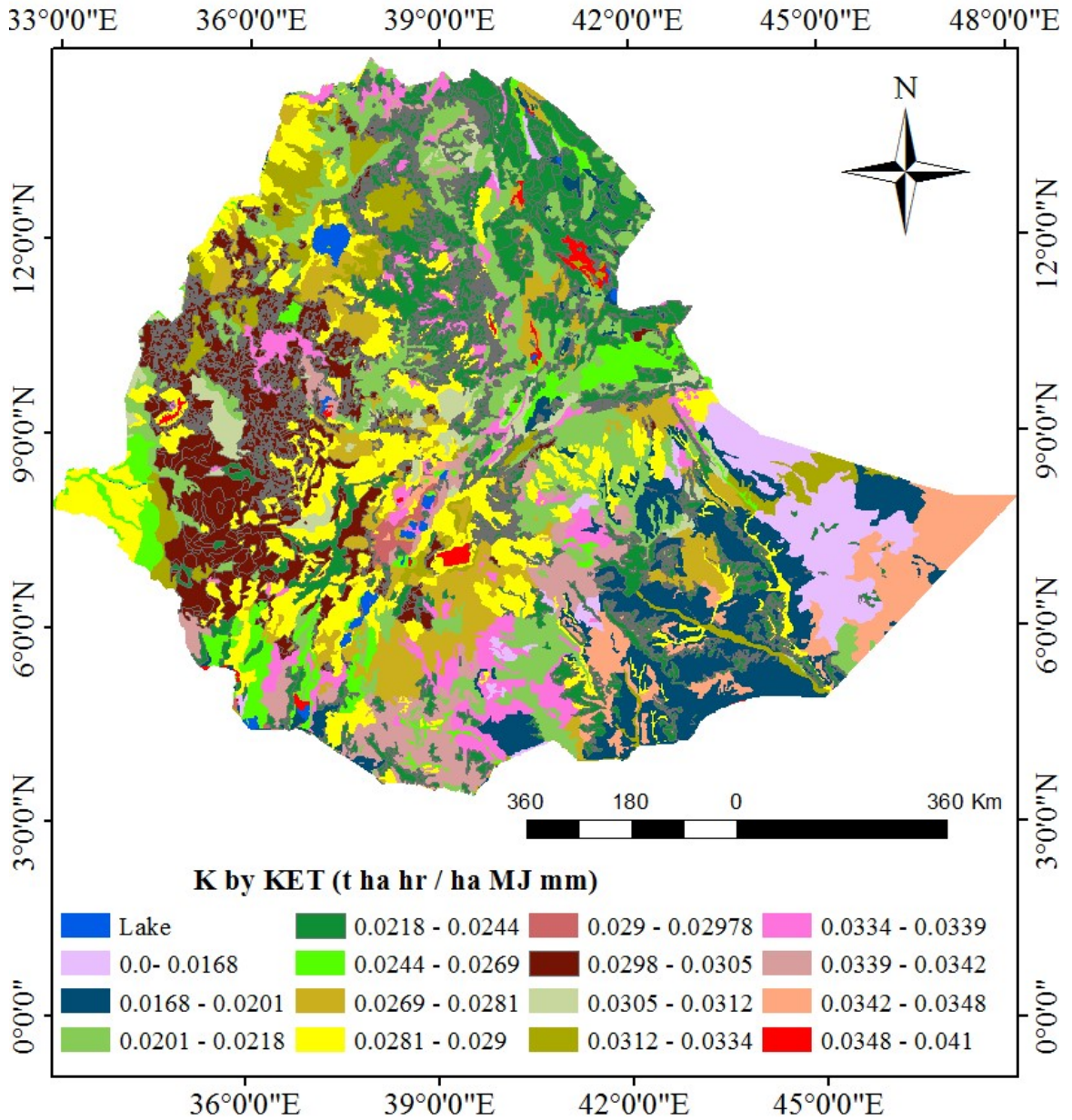


Figure 5 11 The Soil erodibility map of Ethiopia

5.5. Conclusion

Soil erodibility, as index for evaluating the difficulty degree of separation, erosion and movement of soil by the erosive force of rain fall, is an internal factor involved in soil loss and is usually measured by K factor. Originally it was established in monograph form by having the relationship between K and soil texture, OM, structure and permeability. By minimizing

the number of soil parameters, [Sharply and Williams \(1990\)](#) developed a formula for calculation of the K factor in Erosion Productivity Impact Calculator (EPIC), relating only the soil texture and organic carbon content, thus simplifying the calculation of the K value. But study have indicated that the K factor is less influenced by soil chemical property than physical properties that show conspicuous spatial variability even under the same soil condition.

Hence based by formula developed for K in EPIC and by using only physical soil properties, an alternative soil erodibility model (KET) was developed. The KET model was developed for the different soil classes in Ethiopia and comparison of the new soil erodibility factor to the values from the EPIC model and field data were made. Soil texture ratio and bulk density data were used to find the correlation with K values. Using the field sample data from the soil survey experiment, the equation was developed for the ERVLB soils as well as for other soil types in Ethiopia. The similarity of results obtained using KET is compared with the results of EPIC-K method and the model performance statistics of their relation is determined as excellent.

Moreover, the applicability of KET is evaluated to total soils units of the country (Ethiopia) by extracting the required soil physical parameters from FAO world soil database and the original K estimation equation derived for EPIC-K model is considered for evaluation of the KET. As a result, the KET is predicting k values for 35.7% of the country soil with a relative error less than $\pm 5\%$. On average, the KET method can be applied for more than 58.9% of the country soils with an average error of $\pm 5.3\%$ and standard deviation of 3.2. For the remaining 41.1% of the country soil, k values were predicted with an error of $\pm 13.31\%$ and standard deviation

of 10.3. The soil erodibility factor estimated with the equation proposed in this study is reliable and can be used for ERVLB soils as well as for others soils within the country.

Lastly, when KET compared with K factor developed for EPIC model, it does not require organic carbon content (OCC) and it is based on properties of a soil that can be easily measurable. The OCC of a soil is mostly determined by burning the soil samples which its accuracy is always under question. This omission of OCC from KET is advantageous because the propagation of error from sampling and estimating the OCC can be avoided. The soil properties that are required by the KET can be easily obtained in laboratory through dry and wet sieve analysis and by oven drying techniques. Therefore, the newly developed an alternative soil erodibility estimation model can simplifies the cost and time invested in collecting huge data sets from the field. Additionally, it minimizes the propagation of error from impute data set as it is based with few data sets and with easily measurable soil parameters.

6. PRIORITIZING THE LAKE BASIN BASED WITH THEIR SEDIMENT RISK ³

ABSTRACT

To prolong the useful life of lakes and reservoirs, prioritizing watersheds by severity and risk of soil erosion is an essential index to develop sound sediment management plans. This study aims to predict soil erosion risk and sediment yield using Soil and Water Assessment Tool (SWAT) model in Lake Ziway basin, Ethiopia. The SUFI-2 program was applied for a model calibration and the performance of the model was assessed. The catchment prioritization study indicated that some sub-basins having the same soil type and land use but a higher slope gives higher sediment yield. This confirms that, in the basin, the upland is the main source of sediment for the lake hence the variation of sediment yield is more sensitive to terrain slope. Furthermore, the soil conservation scenarios demonstrated in SWAT that reduce the slope length of the watershed by 50% for slope greater than 5% is decreasing the sediment yield of the basin by 55%. Hence, this result can be used as a guideline for decision-makers to apply a suitable method to reduce the erosion load, especially from high erosion rate areas. On selected hotspot erosion areas, the required treatments may include practicing strip planting, terracing, or contour farming to reduce the effect of slope on surface runoff flow velocity and sediment transport capacity.

Keywords: SWAT; watershed prioritization; sediment yield; reservoir sedimentation; bathymetry, Lake Ziway

³ Alemu O. Aga, Bayou Chane and Assefa M. Melesse (2018). Soil Erosion Modelling and Risk Assessment in Data Scarce Rift Valley Lake Regions, Ethiopia. [Water; 10 \(11\) ; PP1-17; doi:10.3390/w10111684](#)

6.1. Introduction

Land degradation and soil erosion is a serious threat in agroecosystems and is one of the main global environmental crises (Gashaw et al., 2017). It has both onsite effects (loss of fertile topsoil) and offsite effects (sedimentation of lake and reservoirs). Loss of top fertile soil will reduce the productive capacity of the land and thereby create risk to global food security. The most significant and broadly impacting effects of sedimentation on lakes and reservoirs are changes in water balances, thereby reducing the live storage of the reservoir (Elsawwaf and Willems, 2012). Reservoir storage is vitally important for agricultural irrigation, power generation, municipal water supply and other uses. To prolong the useful life of lakes and reservoirs, analyzing soil erosion risk is an important task to plan land use and soil conservation measures.

Erosion risk assessment and sediment risk maps, particularly at the catchment scale, provide important insights into the linkage between soil erosion and sediment deposition in the basin. Also, it can be used for various tasks such as the identification of high-risk areas (erosion hot spots), to assess the catchment's average pattern of erosion risks, to identify deposition and deposition patterns, detailed erosion and major concentrated flow areas (Blinkov and Kostadinov, 2010). For land use and soil conservation planners, a soil erosion and sediment risk map is an important index for prioritizing watershed management interventions (Ayele et al., 2017).

In the catchment, sediment supply is heterogeneous in space and time due to its complex interactions of many factors (Yu and Neil, 1994) such as land use/cover, soil type, climate,

landscape, drainage conditions and human activities (Marttila and Bjørn, 2010). And, hence, quantification of soil loss is often difficult and one of the greatest challenges in natural resources and environmental planning (Arekhi et al., 2010; Salsabilla and Kusratmoko, 2017). Due to its complexity, a computer simulation model that considers all of the factors that initiated soil erodibility and erosivity has been developed. For example, Universal Soil Loss Equation (USLE) (Wischmeir, 1965), the Water Erosion Prediction Project (Nearing et al., 1989), Erosion Productivity Calculator (Jones et al., 1991), the Agricultural Non-Point Source Pollution model (Young et al., 1989), the Areal Nonpoint Source Watershed Environment Response Simulation (Beasley et al., 1980), European Soil Erosion Model (Morgan et al., 1998), The Chemicals, Runoff and Erosion from Agricultural Environment Systems (Knisel, 1980), and Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) have been used over many years.

Among these models, the USLE has remained the most practical method for estimating soil erosion potential and to estimate the effects of different erosion factors on soil erosion. USLE has been used for more than 40 years (Dennis and Rorke, 2000; Kinnell, 2000) whereas other process-based erosion models developed afterward have limitations in applicability due to intensive data and computation requirements (Lim et al., 2005). On erosion quantification, USLE cannot indicate the amount of sediment delivered to the downstream points due to its limitation on calculating the sediment delivery ratio (Lim et al., 2005). As a result, more recent physically-based models have been developed to quantify the soil loss rates. Physical-based models have the ability to predicate the soil erosion and sediment delivery ratio.

The Soil and Water Assessment Tool is one of the physical-based models and has many useful components and functions for simulating the water balance, sediment loss and land management practices (Bisantino et al., 2015). SWAT is designed to consider an in-built erosion prediction algorithm (Taguas et al., 2015) that accounts for the spatial variation of the system using soil, land use, terrain, and management practice data inputs to predict catchment soil erosion and sediment yield (Arnold and Fohrer, 2005). Hence, it is widely used for erosion modeling in several catchments, under different climatic conditions, including semiarid climate. Its performance was tested in different parts of the world. For example, its ability was tested in sediment prediction for the Warner Creek watershed located in Maryland and the evaluation result indicates the existence of strong agreement between yearly measured and SWAT simulated sediment load (Chu et al., 2004). Similarly, on Big Creek watershed of Southern Illinois, Muleta and Nicklow (2005) calibrated daily SWAT sediment yield with observed sediment yield concluded that sediment fit seems reasonable. Iowa, Raccoon River watershed, Jha et al. (2007) found that the sediment loads predicted by SWAT were consistent with sediment loads measured. It was also tested and used in many regions in Africa (Dessu et al., 2014; Dessu and Melesse, 2012, 2013; Setegn et al., 2009, 2010; Setegn et al., 2011; Setegn et al., 2010; Yesuf et al., 2015) to estimate sediment yields from both gauged and ungauged watersheds and good results were reported. Similarly, the performance of SWAT model was tested in Germany (Nguyen et al., 2018), UAS (Parajuli et al., 2009), China (Chang et al., 2015; Guo et al., 2018; Li et al., 2018; Mishra et al., 2018; Qi et al., 2017) and Jamaica (Grey et al., 2014) to predict the amount of sediment as well as stream flow from gauged and ungauged river basins.

Due to its wide applicability, SWAT model was selected in this study to estimate the sediment yield of Lake Ziway basin, Ethiopia. The SWAT model is a watershed scale model that incorporates the features of several other models (Neitsch et al., 2005). Identification of erosion-prone areas using a distributed physical model that estimates soil erosion rates with sufficient accuracy will be important for implementing appropriate erosion control practices (Anwar et al., 2015). SWAT has the ability to estimate erosion at different spatiotemporal scales and small contributing sub-catchments; moreover, modeling errors will be adjusted by calibrating the sensitive catchment flow and sediment parameters related to surface soil and cover conditions. The model's ability to predict catchment soil erosion and sediment yield at different scales from small to large basin-scale studies (Arnold et al., 1995; Grey et al., 2014; Hunink et al., 2013; Juliana and Melesse, 2015; Maalim and Melesse, 2013; Mekonnen and Melesse, 2011; Msaghaa et al., 2014; Wang et al., 2008) and its ability to estimate the spatial heterogeneity in different land management practices are additional benefits (Ayele et al., 2017).

To increase the productivity of the land and to decrease siltation rates of the water body, it is crucial to implement watershed management activities inside the basins. Because of resource limitations, implementing soil conservation measures in the entire basin at a time is impractical. Hence, prioritization of intervention areas based on the severity and risks of soil erosion is imperative. For example, in Ethiopia, the intervention for soil conservation has been exerted since the 1970s (Haregewey et al., 2012). However, the efforts did not bring significant changes to ongoing soil degradation problems of the country (Gashaw et al., 2017; Haregeweyn, Berhe, et al., 2012). Most recently, watershed management is an approach followed by the government of Ethiopia to reduce soil erosion in particular and to reverse land

degradation in general (Haregeweyn et al., 2012; Tongul and Hobson, 2013). Although dramatic reduction has been made in arresting soil erosion (Gashaw et al., 2017; Tongul and Hobson, 2013), the approach has not been supported with intervention prioritizing techniques that identify highly susceptible erosion prone areas. The Lake Ziway basin is one of the central highland basins in the Rift Valley region of Ethiopia where soil erosion is rampant. Hence, to solve this, there is a need to identify the most erosion-sensitive areas in the basin, so that effective conservation measures can be taken. Therefore, the objectives of this chapter are:

- To identify and prioritize erosion hotspot sub-catchments on the basis of estimated runoff and sediment yield;
- To quantify the amount of coarse sediment delivered into the lake from contributing sub-catchments; and
- To suggest suitable land management options for alleviating soil degradation problems.

6.2. Methodology

6.2.1. SWAT model

SWAT is a physical-based model that simulates surface runoff, soil erosion and sediment delivery in a river system (Arnold et al., 1998). It can be used for both gauged and un-gauged basins to estimate the runoff, sediment and chemical yields (Arnold and Fohrer, 2005) with varying land-use, soil, topography and land management practices for long periods of time on a daily (Neitsch et al., 2011).

The model is suitable to simulate a single basin or multiple hydrologically connected basins. The model will divide the basin into sub-basins based on the size of the basin, the spatial detail of available input data and the amount of details required. Further, the sub-basins will be divided into small portions called “hydrological response units” (HRUs), characterized by uniformity of soil and land-use (Msaghaa et al., 2014; Setegn et al., 2009). Hydrological processes are simulated in detail for each HRU and then aggregated for the sub-basin by a weighted average. In SWAT, the hydrologic cycle of a sub-basin is simulated based on the following water balance equation (Msaghaa et al., 2014; Setegn et al., 2009).

$$SW_t = SW_o + \sum_{i=1}^t (R_{\text{day}} - Q_{\text{surf}} - E_a - W_{\text{seep}} - Q_{\text{gw}}) \quad (6.1)$$

where, SW_t is the final soil water content; SW_o is the initial soil water content (mm); t is time; R_{day} is the amount of precipitation; Q_{surf} is the amount of surface runoff; E_a is the amount of evapotranspiration; W_{seep} is the amount of water entering the vadose zone from the soil profile; and Q_{gw} is the amount of return flow.

SWAT calculates the surface runoff from daily rain fall by using modified SCS curve number method (Setegn et al., 2010). The surface runoff component of the water balance is determined from the SCS method as:

$$Q_{\text{surf}} = \frac{(R_{\text{day}} - I_a)^2}{R_{\text{day}} - I_a + S} \quad (6.2)$$

where $I_a = 0.2S$ and $S = 25.4 (1000/\text{CN}-10)$; hence the amount of surface runoff is equated as

$$Q_{\text{surf}} = \frac{(R_{\text{day}} - 0.2S)^2}{R_{\text{day}} + 0.8S} \quad (6.3)$$

where I is initial abstraction (mm), S is relation parameter (mm) and CN is curve number.

SWAT can also calculate the sediment rate from each HRU by using the Modified Universal Soil Loss Equation as the following equation (Williams, 1975).

$$\begin{aligned} \text{Sed} = & 11.8 \times (Q_{\text{surf}} \times q_{\text{peak}} \times \text{Area}_{\text{hru}})^{0.56} \times K_{\text{USLE}} \times C_{\text{USLE}} \\ & \times P_{\text{USLE}} \times LS_{\text{USLE}} \times \text{FRG}_{\text{USLE}} \end{aligned} \quad (6.4)$$

where, Sed is yield of sediment in t/day; Q_{surf} is Volume of surface runoff (mm/ha); q_{peak} is the greatest surface runoff rate (m^3/s); Area_{hru} is Hydrologic response unit area (ha); K_{USLE} is USLE soil erodibility factor; C_{USLE} is USLE topography factors cover; LS_{USLE} is USLE topography factors and P_{USLE} is USLE soil protection factors; and CFRG accounts for stoniness.

For channel networks, SWAT computes the sediment flow as (Neitsch et al., 2011):

$$\text{Sed}_{\text{ch}} = \text{Sed}_{\text{ch},i} - \text{Sed}_{\text{deep}} + \text{Sed}_{\text{deg}} \quad (6.5)$$

where Sed_{ch} is the amount of suspended sediment in the reach; Sed_{deg} is the amount of sediment that reenters the reach segment; Sed_{dep} is the amount of sediment deposited in the reach segment; and $\text{Sed}_{\text{ch},i}$ is the amount of suspended sediment in the reach at the beginning of the time period.

Similarly, SWAT calculates the amount of sediment transported out of reach as (Neitsch et al., 2005):

$$\text{Sed}_{\text{out}} = \text{Sed}_{\text{ch}} \times (V_{\text{out}} / V_{\text{ch}}) \quad (6.6)$$

where Sed_{out} is the amount of sediment transported out of the reach; Sed_{ch} is the amount of suspended sediment in the reach; V_{ch} is the volume of water in the reach segment, and V_{out} is the volume of outflow during the time step.

6.2.2. Model development and input description

To develop the SWAT model, two types of dataset are required: meteorological and catchment characteristics datasets (topography, soil and land use maps).

To set up a SWAT model for our study Area, 30 m × 30 m digital elevation model (DEM), land use map, soil maps and soil laboratory analyzed results of the basin major soils types were obtained from the Ministry of Water Irrigation and Electricity of Ethiopia (MoWIE). Prior to the application of the maps in the model, preprocessing work was carried out. The land use map has been re-classified into SWAT land use classes. The soil properties required to set up SWAT-model is soil texture, grain size percentage, soil saturated hydraulic conductivity, bulk density, soil available water and texture class. Therefore, these soil characteristics were obtained from a laboratory analyzed result done under Rift Valley Lake Basin Master Plan study document (MOWR, 2010). During the study of Ethiopian Rift Valley Lake Basin Master Plan, the soil samples were collected from all soil units of the basin and its physical and chemical laboratory analyses were conducted in the Ethiopia Water Works Design and Supervision Enterprise (WWDSE) laboratory. From out of 13 soil units of the basin, 203 soil samples were collected and its physical and chemical properties were analyzed. Hence, the soil database of the SWAT model was set-up for the basin using the analyzed soil properties. The basin's soil erodibility (K) factor was calculated using the equation shown in EPIC (Sharply and Williams, 1990) from the analyzed soil parameters.

The meteorological data included daily precipitation, maximum and minimum temperature, daily wind speed, daily sunshine hours and daily relative humidity, and they were obtained from meteorological stations (Figure 2.3) available within and nearby the study area. Daily data of 31 years (1987–2017) were collected for the study.

To fill the missing values of climate elements, a weather generator model was used. The required statistical parameters were computed using the computer program developed by [Liersch \(2003\)](#). In the Lake Ziway basin, two meteorological stations (Ziway and Bui) were analyzed and used to establish the weather generator database.

6.2.3. Sub-watershed delineation

Katar and Maki Rivers are the two major tributary rivers in Lake Ziway watershed. Before joining the lake, there are stream gauging stations namely Maki and Abura along the Maki and Katar Rivers, respectively. Using the 30×30 m resolution DEM data, contributing areas upstream of the two stations were delineated using ArcGIS 10.2 (Esri, Redlands, CA, USA). Accordingly, the entire study area has been divided into 51 sub-watersheds of which 26 are inside Maki and 25 in Katar Rivers sub-basins. Based on the model setup with land use, soil and slope, and minimum area threshold values set as 5%, 10% and 10%, respectively, 550 Hydrological Response Units (HRU) were identified, which are unique combinations of land use, soil type and slope (Figure 6.1).

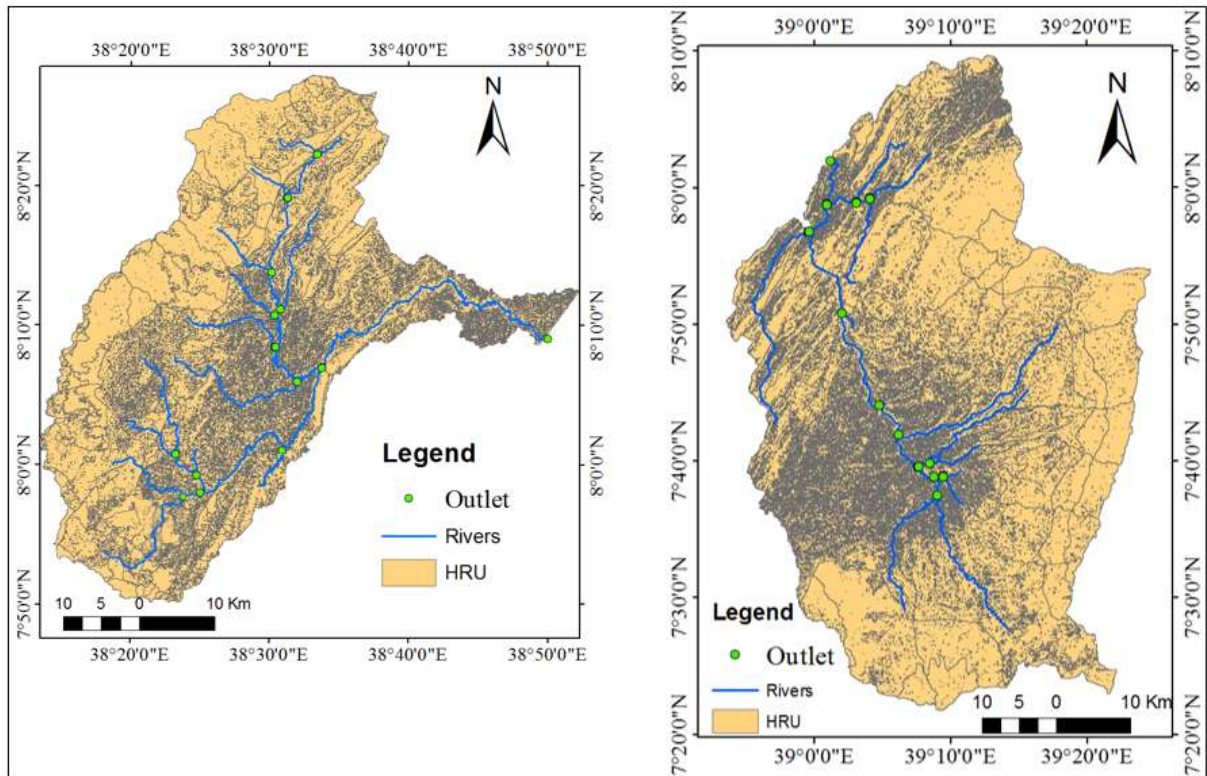


Figure 6. 1 Hydrologic response unit (HRU): Maki (Left) and Katar (Right) Sub-watersheds

6.2.4. Model calibration and validation

To calibrate and validate the model, the daily stream flow data was obtained from MoWIE and the sediment data were generated by using sediment-discharge rating curves developed for the sites (Chapter 3 of this Study). As SWAT simulates total sediment load including bed load, it is necessary to include the bed load component on the suspended load to have total sediment load for the model calibration and validation. However, in most studies in Ethiopia, the bed-load component is frequently ignored due to measurement constraints. In most rivers, bed load to suspended load ranges from 10 to 30% (Church, 2006). Maki and Katar flow on a moderate to gentle slope throughout their course. Hence, we assumed the bed-load as 10% of the suspended sediment load obtained from the rating curve and added for model calibration.

To prioritize the sub-basins based on their sediment contribution, the adequacy of the SWAT model was tested by calibrating and validating the model. For Maki River, at Maki gauging station, the model was run for the simulation period of 1 January 1996 through December 2013. The stream flow and sediment data of 10 years from 1999 to 2008 were used for calibration and the subsequent 5 years (2009–2013) were then used for validation period. Similarly, for Katar River, the model was run for the period of 1987 to 2010 with 11 years (1990 to 2000) calibration and 10 years (2001 to 2010) validation period. For both rivers, the first 3 years in the calibration run were used for model warm-up. In this study, the length of the time period used for calibration and validation were determined based on the existing observed data records. During calibration, sensitivity analyses were conducted automatically using the SUFI-2 program in SWATCUP software.

6.2.5. Data quality control and statistical analysis

Both hydrological and metrological data must be checked for continuity and consistency before it is used for further analysis. The analysis involved data quality assessment and filling of data gaps. The continuous daily series data of each stations were subjected to detect outliers caused by instrumental and/or human errors. Grubbs test method ([Grubbs, 1969](#)) was used to detect the outlier and those either less than half or more than twice the expected amount or concentrations were removed from further analysis. In none of the cases no more than 1% of the data points were discarded.

The model performance for fitting measured constituent data was evaluated by using four widely used statistical indices: coefficient of determination (R^2), Nash–Sutcliffe coefficient (NSE), Percent bias (PBIAS) and RSR (the ratio of root mean square error (RMSE) to the

standard deviation of the measured data). The goodness of fit for model performance was based on [Moriassi et al. \(2007\)](#).

6.3. Results and Discussion

6.3.1. Flow calibration and validation

A sensitivity analysis was conducted and 13 major parameters were selected for both sub-catchments (Abura and Maki). To obtain optimal fitting with the measured data, calibration was conducted manually and automatically by SUFI-2 program. The most sensitive parameters identified for both stations during calibration are SCS runoff curve number (CN2.mgt), effective hydraulic conductivity in main channel (mm/hr) (CH_K2.rte), saturated hydraulic conductivity (mm/hr) (SOL_K.sol), Ground water “revap” coefficient (GW_REVAP.gw), available water capacity of the soil layer (mm H₂O/mm soil) (SOL_AWC.sol), surface runoff lag time (SURLAG.bsn), threshold depth of water in the shallow aquifer required for return flow to occur (mm) (GWQMN.gw), soil evaporation compensation factor (ESCO.hru), slope of water shed (HRU_SLP.hru), base flow alpha factor (days) (ALPHA_BF.gw), groundwater delay (days) (GW_DELAY.gw), Plant evaporation compensation factor (EPCO.hru), and moist bulk density (SOL_BD.sol) with different sensitivity ranks (Table 6.1). The sensitivity result shows the SCS runoff curve number (CN2.mgt) as a major critical parameter for both stations. Curve number in a watershed is directly related to land use/cover and soil characteristics.

Table 6. 1 Parameters sensitivity rank based on P-value and t-stat

Parameter	Description	Range	Maki Sub-watershed	Katar Sub-watershed
			Sensitivity Rank	Sensitivity Rank
CN2.mgt	Initial SCS CN II value	35-98	1	1
SOL_K.sol	Saturated hydraulic conductivity	0-2000	8	2
HRU_SLP.hru	Average slope steepness (%)	0-60	5	3
CH_K2.rte	Channel hydraulic conductivity	5–130	11	4
GW_REVAP.gw	Ground water “revap” coefficient	0-0.2	12	5
SOL_AWC.sol	Available water capacity	- 0.2– 0.4	6	6
SURLAG.bsn	Surface runoff lag time (days)	1-12	7	7
GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0-5000	3	8
ESCO.hru	Soil evaporation compensation factor	0.01–1	2	9
GW_DELAY.gw	Groundwater delay (days)	0-500	10	10
ALPHA_BF.gw	Base flow alpha factor (days)	0–1	9	11
SOL_BD.sol	Moist bulk density	0-0.25	13	12
EPCO.hru	Plant uptake compensation factor	0-1	4	13

The relative sensitivity (significance) of parameters indicated in Table 6.1 was ranked with t-stat and p-values. t-stat provides a measure of sensitivity and larger in absolute values are more sensitive. On the other hand, P-value indicates the significance of the sensitivity and hence a value close to zero has more significance. Therefore, ranking in both cases (t-stat or P-value) give the same result and the result of model for stream flow calibration and validation in both stations is obtained as Figure 6.2 and 6.3.

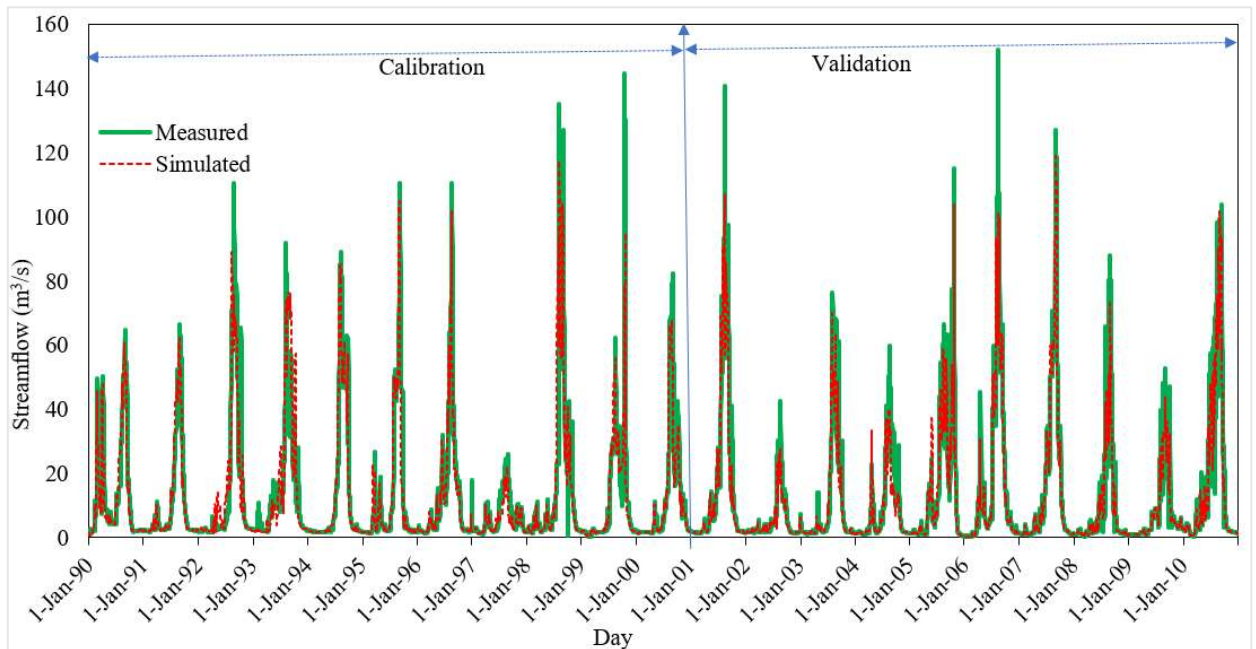


Figure 6. 2 Daily stream flow calibration and validation at Abura gauging station

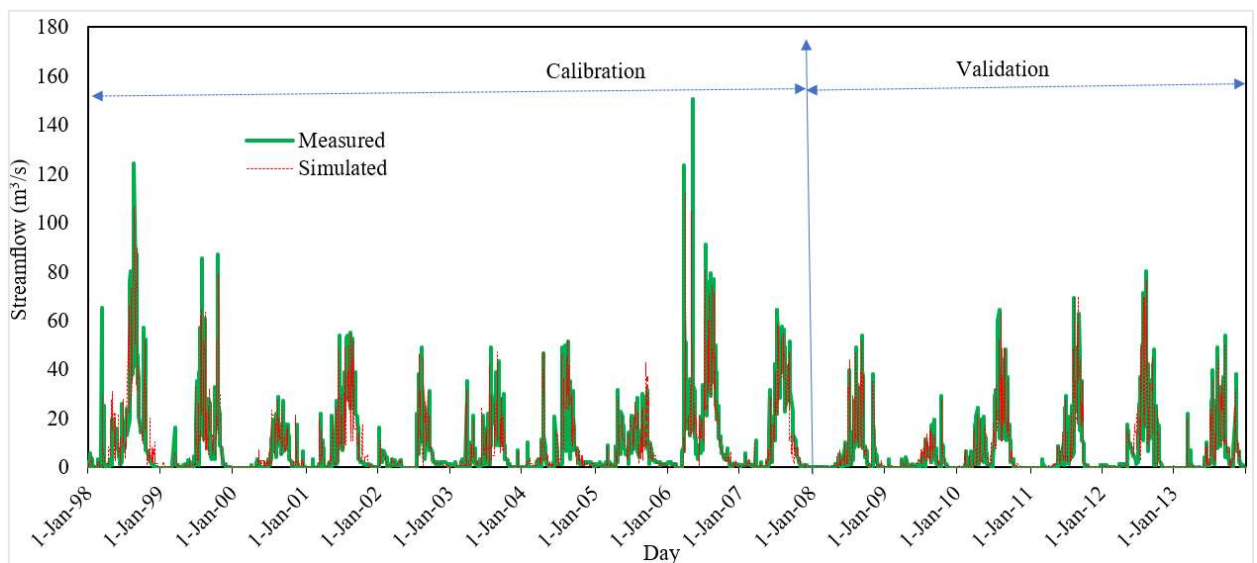


Figure 6. 3 Daily stream flow calibration and validation at Maki gauging station

The graphical representation of measured and simulated daily stream flows matched well for both calibration and validation periods (Figures 6. 2 and 6.3). The goodness-of-fit analysis of the calibration and validation stages is shown in Table 6.2. As shown in Table 6.2, all the numerical model performance indicators designated for the model performance evaluation are

concordant with NSE values from 0.71 to 0.85, R^2 values from 0.72 to 0.86, and RSR from 0.39 to 0.54 in the basin. Hence, all numerical model performance measures are in the acceptable range that the SWAT model accurately simulated the measured stream flow on both stations. SWAT developers recommend an acceptable calibration for hydrology at a $R^2 > 0.6$, $NSE > 0.5$ and $RSR < 0.7$ (Santhi et al., 2001). Similarly, its performance is very good compared with the statistical performance value recommended by Moriasi et al. (2007).

Table 6. 2 Daily streamflow calibration and validation model performance statistics

Parameter	Maki Sub-Basin (At Station Maki)		Katar Sub-Basin (At Station Abura)	
	Calibration	Validation	Calibration	Validation
NSE	0.73	0.71	0.79	0.85
R^2	0.74	0.72	0.80	0.86
RSR	0.52	0.54	0.45	0.39

6.3.2. Sediment yield calibration and validation

After stream flow calibrations, sediment flow calibration was conducted using sensitive parameters related to soil loss from each HRU. To determine the magnitude of catchment sediment yield, initial sensitive sediment parameters were calibrated using the global sensitivity analysis procedure. Besides, six sensitive sediment parameters were identified. Those are USLE support practice factor (USLE_P.mgt), USLE equation soil erodibility (K) factor (USLE_K.mgt), Channel Erodibility factor (CH EROD.rte), Exponential factor for channel sediment routing (SPEX_P.bsn), Linear factor for channel sediment routing (SPCON.bsn) and Channel Cover factor (CH COV.rte).

As shown in Figures 6.4 and 6.5, for both stations, calibration of the SWAT model was successfully achieved using the observed daily sediment flow. Similarly, during the validation stage, the SWAT model mimicked well the sediment inflow from the two tributaries.

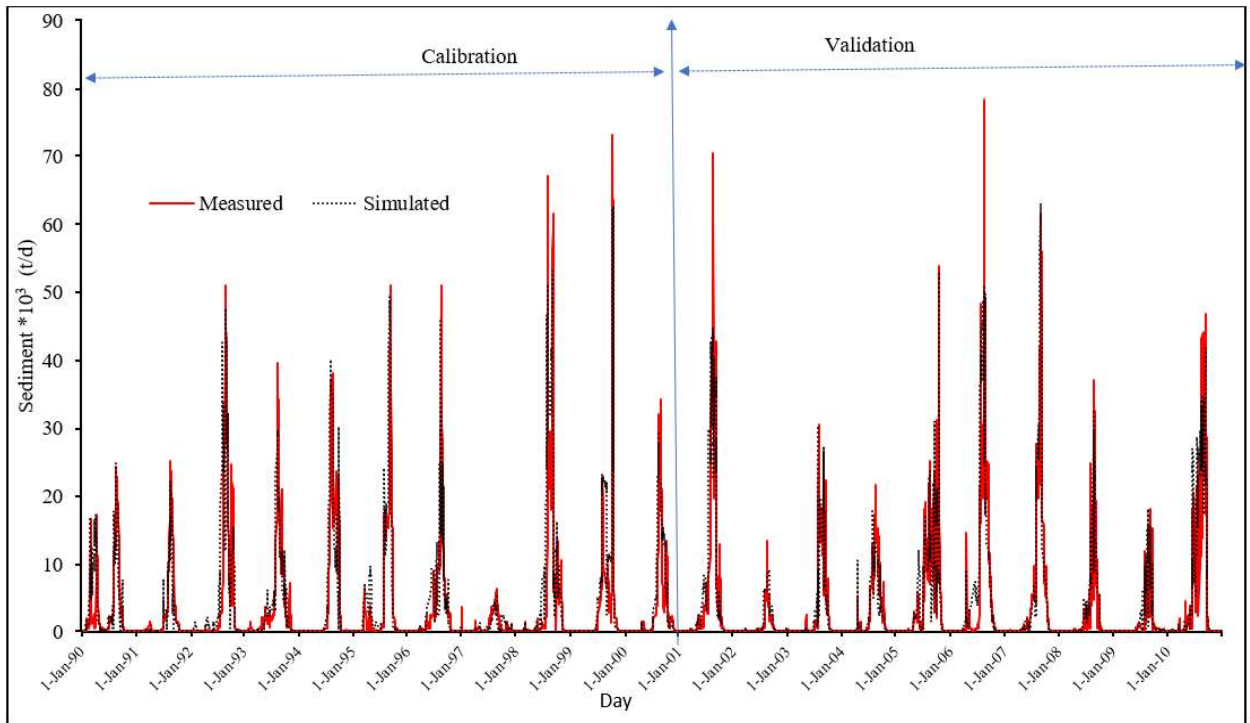


Figure 6. 4 Sediment yield calibration and validation at Abura gauging station

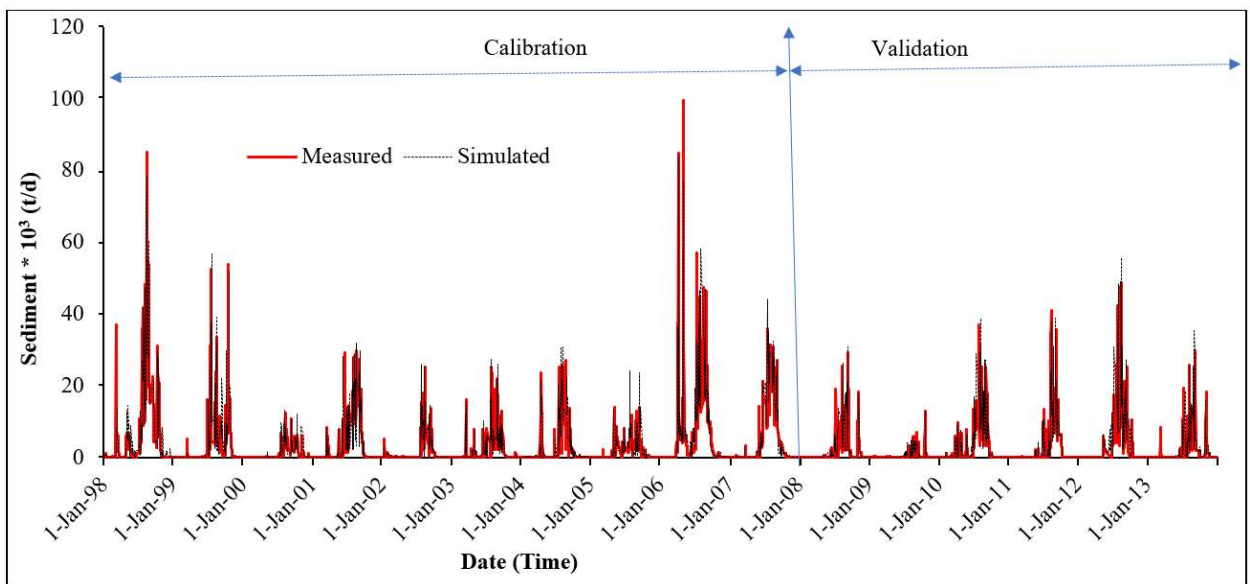


Figure 6. 5 Sediment yield calibration and validation at Maki gauging station

Based on the calibration and validation results, the model performance was evaluated in terms of the statistical indicators (Table 6.3).

Table 6. 3 Daily measured and simulated sediment yield calibration and validation model performance statistics

Parameter	Maki Sun-Basin (At Station Maki)		Katar Sub-Basin (At Station Abura)	
	Calibration	Validation	Calibration	Validation
NSE	0.74	0.75	0.72	0.79
R ²	0.71	0.71	0.67	0.75
PBIAS	-7.87	-12.25	-16.68	-16.25
RSR	0.54	0.53	0.58	0.50

As can be seen in Table 6.3, all numerical model performance measures are in the acceptable range indicating that the SWAT model replicates the measured sediment yields. Similarly, the graphical representation of measured and simulated flows matched well for both calibration and validation periods (Figures 6.4 and 6.5). Hence, the result can be used to identify major sediment source areas within the sub-watersheds.

6.3.3. Spatial distribution of sediment generation hotspot area

The calibrated SWAT modeled was used to simulate the effect of management/conservation measures on water and sediment yield in Lake Ziway basin. The spatial variability of erosion rate was identified as Figure 6.6.

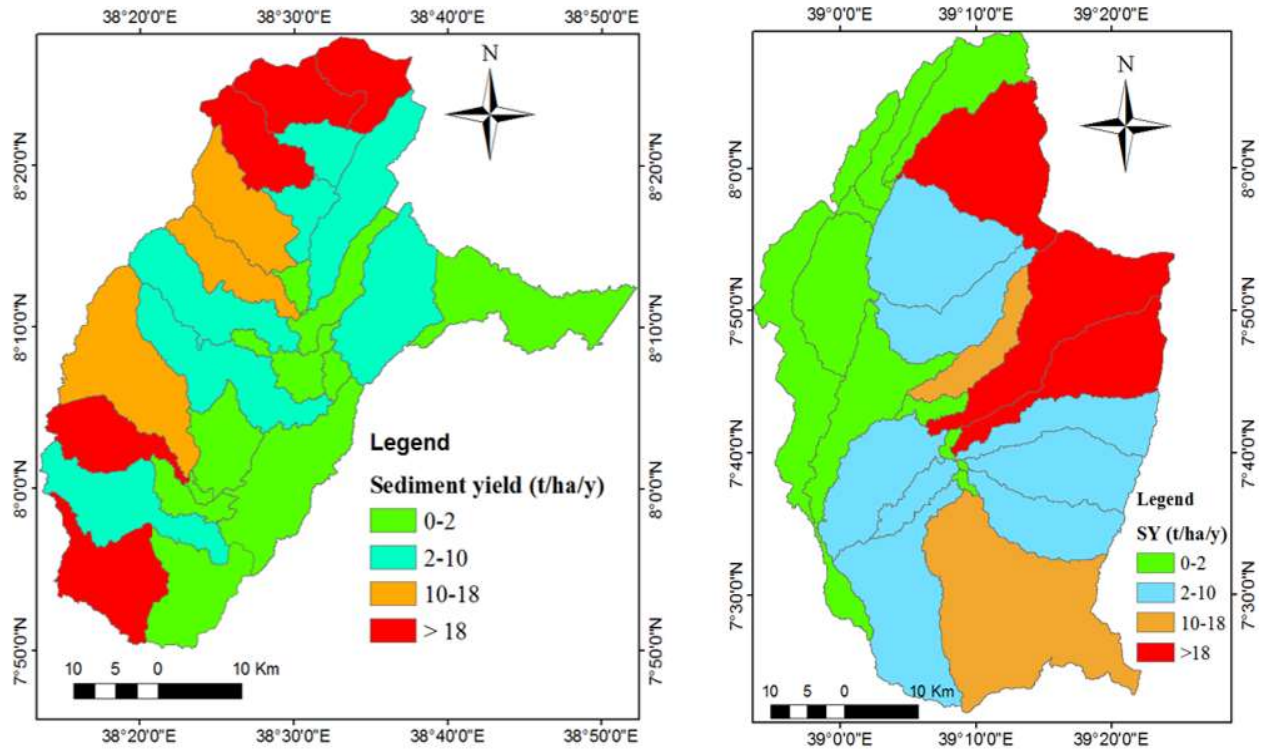


Figure 6.6 Spatial distribution of soil loss severity classes: Maki (Left) and Katar (Right) sub-watersheds

To quantify the effects of the spatial distribution of soil type, land use and terrain slope on soil erosion, seven main erosion source areas ($SY > 18$ t/ha/year and indicated in red color in Figure 6.6) inside of Maki and three inside of Katar sub-basins were selected (Figure 6.6). For both sub-basins, all the selected catchments were characterized by a single land use class (agriculture) and one dominant soil type of Luvisols. In addition, the research employing catchment prioritization indicates that in low land areas with the same land use and soil type, the soil loss is low. This indicates that the variation of sediment yield is more sensitive to terrain slopes due to poor land use practices on steep slope areas.

Based on this result, potential areas of intervention were prioritized and three management or conservation measurement scenarios were developed and simulated using SWAT model in order to evaluate the most suitable management/conservation measures within the basin.

- ☞ Base Scenario (Scenario 1): This scenario presents the actual condition observed in the watershed (without conservation measures)
- ☞ Scenario 2: Assume the slope length of the watershed is reduced by 25% for a slope greater than 5% by using physical conservation structures (Parallel Terraces, Fanya Juu, soil bund, etc.)
- ☞ Scenario 3: Assume the slope length of the watershed is reduced by 50% for a slope greater than 5% by using physical conservation structures (Parallel Terraces, Fanya Juu, soil bund, etc.)

Simulation was performed for each scenario for the HRUs with the corresponding conservation measures and management practices. The sediment yields were compared to the result of the baseline scenario simulation. Sediment loss reductions relative to the base scenario due to conservation practices are listed in Table 6.4.

Table 6. 4 Estimated sediment reduction due to conservation structures and best management practices as compared to the baseline scenario

Scenario	Percentage of Change in Sediment Flow	
	Maki Sub-Basin	Katar Sub-Basin
Base scenario	0	0
Scenario 2	-13	-12
Scenario 3	-55	-49

As shown in Table 6.4, for Maki sub-basin, scenario 3 is reducing the sediment yield by 55% and scenario 2 by 13%. Similarly, for Katar sub-basin, scenarios 3 and 2 reduce the sediment yield by 49 and 12%, respectively. On average, the sediment yield of Lake Ziway basin will reduce by 52 and 12.5% of scenario 3 and 2, respectively. Due to the different slope ranges between the two sub-basins, with equal slope length reduction, the effectiveness of sediment reduction has varied.

Hence, this result can be used as a guideline for decision-makers to apply a suitable method to reduce the erosion load, especially from high erosion rate areas. On selected hotspot erosion areas, the required treatments may include practicing strip planting, terracing, or contour farming to reduce the effect of slope on surface runoff flow velocity and sediment transport capacity.

6.4. Conclusions

The aim of this study was to assess surface runoff generation and soil erosion rates for Lake Ziway basin by applying the SWAT model. Field measured soil parameters were used for calibrating and validating both runoff and sediment flows. The calibration processes considered sensitive flow and sediment parameters to evaluate the degree of agreement between measured and simulated monthly datasets. The model performance was evaluated using statistical indices and was found to be very good for both flow and sediment on both calibration and validation periods.

Sediment yield estimated with the SWAT model was found to correlate reasonably well with soil, land use, and topography for each HRU. Based on the sediment yield of the sub-basins, potential sediment source areas for catchment prioritization and erosion control were identified. All the sub-basins identified as source areas for sedimentation were typified by a single soil type and one land use class with different terrain slopes. This indicates that the variation of sediment yield is more sensitive to terrain slopes due to poor land management in high slope areas. Furthermore, the research showed that the best option to reduce the sediment flow of the basin is applying a soil conservation activity that reduces the basin slope length. For a scenario that reduces the slope length of the watershed by 50% for slopes greater than 5%, the sediment yield of the basin is reduced by 55%.

To reduce the environmental degradation of the basin and prolong the useful life of the lake, a systematic plan and policy will be needed. Hence, the developed map (Figure 6.6) that shows the high erosion area is a tool for decision makers to implement suitable soil conservation measures on selected areas. On selected hotspot erosion areas, the required treatments may include practicing strip planting, terracing, or contour farming to reduce the effect of slope on surface runoff flow velocity and sediment transport capacity.

7. AN ALTERNATIVE EMPIRICAL MODEL TO ESTIMATE THE WATERSHED SEDIMENT YIELD BASED ON HYDROLOGY AND GEOMORPHOLOGY ⁴

ABSTRACT

Physical-based soil erosion models are playing an important role in the assessment soil erosion, transportation and deposition in the watershed. Most of these models were developed for data rich areas of the world and they need a measured data to calibrate and validate their results. To apply such physical-based models, the main factor hindering is the lack of measured sediment data. The amount of sediment in the fluvial systems is the result of hydro-geomorphological processes of a watershed and nature of stream flows. Therefore, this study aims to develop an alternative empirical model that generates the observed sediment data based on the hydro-geomorphology and nature of stream flows for Ziway Lake basin in the rift Valley of Ethiopia. By applying Soil and water Assessment Tool (SWAT), the lake basin was divided in to two sub-basins (Maki and Katar) with 26 of the watersheds within Maki. The SWAT model was calibrated and validated for both stream and sediment flow by using SUFI-2 program and its performance was assessed by using model evaluation statistics. With calibrated sediment flow rates of 26 Maki sub basins, an empirical model was developed by using its respective drainage area, average sub-basins slope, surface runoff, soil erodibility factor, stream flow rate and average rive slopes. The applicability of the newly developed alternative model was tested by using model evaluation statistics and validated inside of Katar sub-basin.

Keywords: SWAT; hydro-geomorphology; alternative empirical model; Lake Ziway; Ethiopia

⁴ Alemu O. Aga, Assefa M. Melesse and Bayou Chane. An Alternative Empirical Model to Estimate the Watershed Sediment Yield Based on Hydrology and Geomorphology of the Basin in Data Scarce Rift Valley Lake Regions, Ethiopia.

7.1. Introduction

Sediment erosion, transport, and deposition in fluvial systems are complex processes (Arekhi et al., 2010; Salsabilla and Kusratmoko, 2017). The erosion of soil from upland areas and deposition of sediment in low land and river banks will depend on hydrology and geomorphology of a watershed (Marttila and Bjørn, 2010). Hydrologic parameters like rainfall depth, intensity, surface runoff and stream flows will play a fundamental role in erosion generation and sediment transportation. Similarly, the production and transportation of sediment in the fluvial system will depends on watershed geomorphological parameters like drainage network (e.g., stream order, stream length, stream number and bifurcation ratio), areal aspects of the drainage basin (e.g., length of overland flow, drainage density and basin shape) and relief aspects (e.g., basin relief, relief ratio, ruggedness number, gradient ratio, basin slope and relative relief) of the channel network and contributing ground slope (Miller, 1953; Schumm, 1956).

An engineering technique used for determination of erosion rate of a watershed relies on two approaches: the upland watershed sediment yield predication approach and instream sediment predicating approach. In both methods, quantification of soil loss is one of the greatest challenges and to overcome its sophistication different models have been developed (Arekhi et al., 2010; Boggs et al., 2001; Salsabilla and Kusratmoko, 2017).

In different parts of the world, different upland watershed sediment yield quantification equations were developed. Such as, Pacific Southwest Interagency Committee Method (PSIAC) (PSIAC, 1996), Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977), Soil Loss Estimation Model for Southern Africa (SLEMSA) (Stocking, 1981), Erosion Potential Method (EPM) (Nearing et al., 1999), Sediment Delivery Distributed (SEDD) (Ferro and Porto, 2000), Modular Soil Erosion System Project (MOSES)(Meyer et al., 2001) and BQART (Syvitski and Milliman, 2007) models have been used over many years. These models are developed for a specific area with the help of statistical observations based on parameters detected in the field (Hajigholizadeh et al., 2018). Hence it may give fairly accurate results if the equation is applied to conditions similar to those from where the equation was derived.

Sediment modeling in the stream channel estimates suspended load, bed load or total load. Different sediment transport equations have been developed for different specific situation of river systems. For example, Blench (1969) and Lacey (1930) developed the equation that estimates the total load of sediment transported in the river-based regime approaches. The regime approach assumes as an alluvial channel in dynamic equilibrium without noticeable long-term aggradation, degradation, or change of channel geometry and profile. These types of equations are useful in stable canals. However, they have been subjected to criticism for their lack of rational physical rigor. Next, some researchers have developed the sediment transport function-based regression approach. They recommend to use the regressions on dominant variables based on laboratory and field data observations. For example, Karim and Kennedy (1990) were proposed the regression equation to determine sediment transported of the steam based on 339 set of laboratory data using nonlinear, multiple-regression analyses to

derive relation between flow velocity, sediment discharge, bed-form geometry, and fraction factor of alluvial rivers. Similarly, [Shen and Hung, \(1972\)](#) were also proposed the regression equation between total sediment transport capacity of the river based with an average falling velocity of sediment particles. In overall, the existing sediment predication formula developed based on regression approach are developed based on laboratory analyzed data. Hence it may give fairly accurate results for engineering purposed if the equation is applied to conditions similar to those from where the equation was derived. Application of a regression equation outside the range of data used for deriving the regression equation should be carried out with caution ([SRHG, 2006](#); [Wilbert, 2009](#)).

To model the sediment transport in the river, [Einstein \(1950\)](#) pioneered sediment transport studies from the probabilistic approach. He assumed that the beginning and ceasing of sediment motion can be expressed in terms of probability. He also assumed that the movement of bedload is a series of steps followed by rest periods. In spite of the sophisticated theories used, the [Einstein \(1950\)](#) transport function is not popular one for engineering application. Around 1966, [Bagnold \(1966\)](#) was developed an equation to predict sediment flow rate in the river based on general physics (stream power approach). He equates the energy required to transport materials should be equivalent to the rate of material being transported. [Engelund and Hansen \(1967\)](#) and [Ackers and White \(1973\)](#) later used the concept of the [Bagnold \(1966\)](#) as a theoretical basis to develop their sediment transport factions. Study by [Yang \(2002\)](#) shows that the equation developed by stream power approach (general physics) is overpricing the transport rate of fine sediments.

Also, many other formulae are developed to predict the bedload rate of the streams by engineers. Those include [Schoklitsch \(1934\)](#) bedload formula that developed based on flume data with medium sediment size, [Kalinske \(1947\)](#) bedload formula that developed based continuity equation [bed load discharge is equal to the product of the average velocity of the particle in motion), [Rottner \(1959\)](#) bedload formula that express the bedload discharge in terms of the flow parameters based on dimensional considerations and empirical coefficients by applying the regression analysis on stream bed roughness parameters, [Einstein \(1950\)](#) bedload formula that developed by the concept of probabilities of particle motion and [Laursen \(1958\)](#) bedload formula that computes the mean concentration of bed-materials discharge based on empirical relation of size fraction of bed material, mean grain diameters of sediment particles, shear velocity and etc. The comparisons of those equations were published by [Brownlie \(1981\)](#); [Yang \(1984, 2003\)](#) and [SRHG \(2006\)](#). The result of these studies indicates that computed sediment load or consternation from different sediment transport formulas give a vastly different results from each other and from field measurements. Hence none of them have elected as universally accepted model.

To simulate and validate the sediment yield of the basin by mathematical and physical based distributed models, observed sediment data could be required. In most developing countries, unavailability of measured sediment data is restricting the applicability of such models. As shown above, there are a lot of empirical models that can predict the sediment yield either in the form of suspended or bed load. But all of them were developed by having laboratory analysis data on controlled environments. Hence, they can give an accurate result for the area where they were developed. Studies like [Yang \(1984, 2003\)](#) have criticized the methods due to having vastly different results from each other. In addition to this, they cannot be applied on

data scarce area like Ethiopia where the availability of sediment laboratory data is limited. Hence the formula that can account the sediment yield without sophisticated (laboratory) data may be needed for further sediment study. Therefore, the main objectives of this study is to develop an empirical model that can predict the sediment yield based with watershed hydrology and geomorphology. The Lake Ziway Basin is considered as a case study and the actual sediment rate of the basin is predicted by GIS based watershed model, Soil and Water Assessment Tool (SWAT) through calibration and validation techniques.

7.2. Methodology

A sediment yield of sub-basin at a point of each sub-basin's outlet can be obtained either by monitoring or by using a conceptual model. Measuring sediment on each sub basin of the watershed is time consuming and expensive. Physically based models can help in obtaining the sediment yield of each sub basin with a limited measured data by using sediment rating curves. A physically based models have a capability to classify the entire area into smaller watersheds (sub basins). SWAT is a good example of a physically based model that can classify the watershed into sub basin and can model both gauged and ungauged parts of the basin. Hence, the SWAT model is selected to create sediment data of the basin.

7.2.1 Sediment data generation

As indicated in Chapter 6 of this study, Lake Ziway has two major tributary rivers namely Katar and Maki and before joining to lake, there is a stream gauging stations namely Maki and Abura along the River Maki and Katar respectively. By using the stream flow gauging locations of both rivers, in ArcGIS 10.2 with ArcSWAT-2012 the spatial heterogeneity of Lake Ziway sub-watersheds were delineated with 30 x 30 m resolution DEM data. Accordingly, the

entire study area was divided into 51 sub-watersheds which composes 26 inside of Maki and 25 inside of Katar Rivers basins (Figure 7.1).

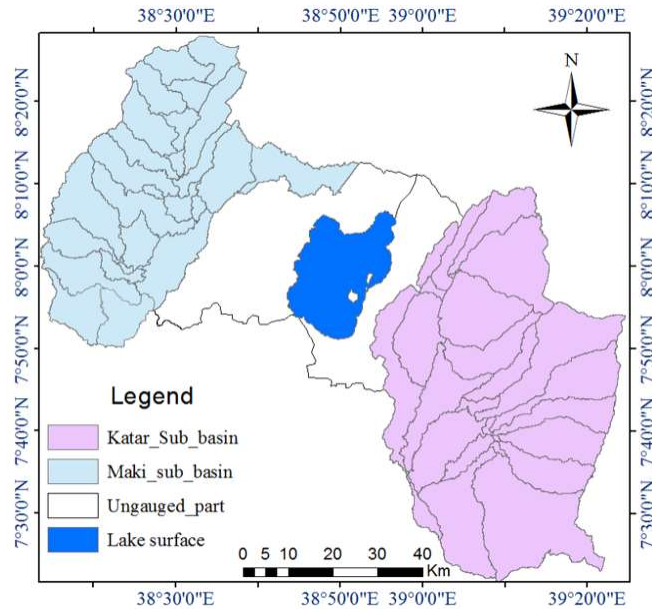


Figure 7. 1 Delineated sub basins of Ziway Lake by SWAT model

Moreover, in Chapter 6 of this study, for both river basins (Maki and Katar) the SWAT model was celebrated and validated for stream flow as well as sediment flow in acceptable ranges (Figure 6.2 to 6.5). Hence, the model result determined was taken as an impute parameter to develop an alternative empirical model that can substitute the measured data for the site.

7.2.2 Identification of geomorphological parameters that govern the sediment yield

The erosion of soil from upland areas and deposition of sediment in low land and river banks is primarily governed by hydrology and geomorphology of a watershed. The geomorphology of a watershed refers to its physical characteristics. The main geomorphologic factors are: area, elongation ratio, shape factor, slope and hypsometric integral. Hence these parameters were detected by using SWAT-2012. For the parameters that could not be detected with the

SWAT2012, GIS spatial analysis tools were used. The elevation values of each watershed were determined from the DEM data of the study area. This was carried out with GIS spatial analysis tools by generating a contours map and extracting the respective elevations, maximum, minimum as well as average elevation for each sub watersheds. The extracted elevation values were used to compute basin relief (R) and hypsometric integrals (Hi), while area, slope and watershed length parameters were obtained from the watershed configuration output data in SWAT2012. Sub-basin shape factors (Fs) and elongation ratios (Re) were calculated by using their respective formulas (Table 7.1).

Table 7. 1 Standard methods of morphometric parameters

Morphometric Parameters	Methods and Descriptions	References
Stream length (SL)	Length of the stream	(Horton, 1945)
Hypsometric integral (Hi)	$H_i = (H-h)/(H_{mean}-h)$; H is maximum elevation and h is minimum elevation and Hmean is mean elevation of the watershed	(Horton, 1932)
Elongation ratio (Re)	$Re = 2/Lb * (A/\pi)^{1/2}$ (The ratio of the diameter of a circle having the same area as a considered watershed and the maximum length of the watershed)	(Schumm, 1956)
Basin relief (Rb)	$R = H-h$; H is maximum elevation and h is minimum elevation within the basin	(Schumm, 1956)

Basin Slope (S)	$S = H/Lb$, (The ratio of the change in elevation between the furthest point of watershed outlet and the watershed length is the slope)	(Miller, 1953)
Shape factor (Fs)	$F_s = L^2/A$ L is the length of the watershed; and A is the area of the watershed	(Horton, 1932)

To develop an alternative sediment predicating empirical formula, the interrelated sediment flow with basin hydro-geomorphological parameters was developed for Maki sub basin. Maki river basin was classified in to 26 sub basins and during SWAT calibration and validation (Figure 7.1). Hence the stream flow and sediment yield were extracted from calibrated SWAT2012 result (Figure 6.3 and 6.5). With the availability of the parameters and the sediment yield from the SWAT2012 model calibration, statistical analysis has been carried out to evaluate the level of dependence of the watershed sediment yield on the hydrologic and geomorphologic factors. Pearson's correlation was applied by using SPSS statistical software to identify the most correlated factors. The sample correlation matrix computed for month July of the year 2010 is indicated in Table7.2.

Table 7. 2 Sample sediment correlation matrix with different parameters for month of July 2010

Pearson Correlation	SY	A	Sw	Re	Fs	Hi	SL	Sr	Q
SS	1	0.69**	0.897**	0.79**	0.245	0.396*	0.847**	0.853**	0.868**
N	26	26	26	26	26	26	26	26	26

** . Correlation is significant at the 0.01 level (2-tailed).

* . Correlation is significant at the 0.05 level (2-tailed).

where SY= Sediment flow in 10^3 ton/day in month July 2010, A is area m^2 , Sw is Mean watershed slope (%), Re is Elongation ratio, Fs is Shape factor, Hi is Hypsometric integral, SL is Stream length (m), Sr is Slope of the river (%) and Q is Flow of each basin on month July (m^3/s).

The statistical analysis indicates that the geomorphologic factors of watershed area, slope and elongation ratio, and the hydrologic factor of stream discharge play a fundamental role in sediment outflow. The more elongated the watershed is the more likely the rate of sediment deposition occurs, if sufficient gradient is not available to drive the sediment load to the river networks.

To develop the empirical formula that handles the sediment rate of the basin, the factors were classified in to two. Upland watershed factors that include the morphology (Table 7.2), surface run off and soil erodibility rate of basin; and instream parameters that includes stream flow and stream average slope.

Surface runoff is a function of soil type, land cover and rainfall amount of the basin. To predict this, Soil Conservation Service Curve Number (SCS-CN) model was used. The SCS-CN method computes direct runoff through an empirical equation that requires the rainfall and a watershed coefficient as inputs. The watershed coefficient is called as the curve number (CN), which represents the runoff potential of the land cover soil complex. Land use and treatment classes are used in the preparation of hydrological soil-cover complex, which in turn are used in estimating direct runoff. The relation of land use, treatment and soil hydrological group is given in [USDA \(1972, 2004\)](#) and [Melesse et al. \(2003\)](#) for different types of land use.

CN in dry and wet condition needs an adjustment for antecedent moisture condition (AMC). AMC is an indicator of watershed wetness and availability of soil moisture storage prior to a storm, and can have a significant effect on runoff volume ([USDA 1972, 2004](#)). Three levels of AMC are used in the CN method: AMC-I for dry, AMC-II for normal, and AMC-III for wet conditions. The CN values documented for the case of AMC-II and to adjust the CN for the cases of AMC-I and AMC-III, the following equations developed by [Chow et al. \(2002\)](#) for an adjustment.

$$CN_{(I)} = \frac{4.2 * CN_{(II)}}{10 - (0.058 * CN_{(II)})} \quad (7.1)$$

$$CN_{(III)} = \frac{23 * CN_{(II)}}{10 + (0.13 * CN_{(II)})} \quad (7.2)$$

where, $CN_{(II)}$ is the curve number for normal condition, $CN_{(I)}$ is the curve number for dry condition, and $CN_{(III)}$ is the curve number for wet condition.

To determine the curve number and surface runoff coefficient, the soil and land use map obtained from MoWR were employed. For all soil class of the basin, both physical and chemical tests were done by MoWR and the lab results of the tests were obtained from MoWR. By using these characteristics, and mainly relying on soil texture and depth, the map of hydrological soil group of basins according to standard definitions of SCS (soil conservation services) were prepared. In the tables pertaining to curve number for various land use and hydrological soil groups, the amount of CN (Curve Number) was determined and presented in (USDA 1972, 2004; Chow et al. 2002). Then regarding to the land uses and hydrological soil groups of the basin, the amount of CN for conditions of primary moisture average (mode II) was calculated. For preparing the map of basin CN, in GIS 10.2, land use map and hydrological soil groups were combined together and the final map of curve number in years 2010 was obtained. Lastly, the runoff coefficient based with determined CN is produced and prepared as runoff coefficient map for the year 2010. The basin's surface runoff was calculated as:

$$S = \left(\frac{24500}{CN} \right) - 254 \quad (7.3)$$

$$Q = (P - 0.2S)^2 / (P + 0.8S) \quad (7.4)$$

$$CN = (S * (C_i * A_i)) / A \quad (7.5)$$

where, CN is a weighted curve number, CN_i is a curve number from 1 to any no. N, A_i is area with curve number CN_i and P is rainfall (mm)

Lastly, to predicate soil erodibility rate of the basin soil, the soil erodibility equation developed in this study (Chapter 5, Equation 5.7) was used.

7.3 Model development

The watershed sediment yield can be described as a function of the different parameters namely: hydrologic and geomorphologic factors. To establish an empirical model, DataFit model with the version of 9.0 was used. DataFit is a tool used to perform nonlinear regression (curve fitting), statistical analysis and data plotting with up to 20 independent variables. The empirical formula between sediment yield (SY) and watershed geomorphological and hydrological parameters were determined using nonlinear regression equation (Equation 7.6) in Datafit model.

$$SY = \text{function (geomorphology and hydrology)} \quad (7.6)$$

Mathematically, the parameters in Equation 7.6 is equated as:

$$SY = X (Q_s^b * A * S_b * K) + Y (q_r^d * S_r) \quad (7.7)$$

where SY = sub basin sediment yield (tone/month)

Q_s is surface runoff (m^3/s), A is area of each sub basin (km^2), S_b is average slope of each sub basin (%), K is soil erodibility factor of the soil ($t \text{ ha hr/ha MJ mm}$), q_r is stream flow (m^3/s), S_r is average slope of the river (%), X and Y are constants from regression equation; and b and d are peak flow adjustment factors.

To develop the model, for each (26) sub basins, the values of CN, watershed slope, mean average rain fall, soil edibility rate and drainage area were extracted by using ArcGIS 10.2. The mean monthly average rain fall was determined by using IDM from metrological gauging stations located near to basin (Figure 2.4). The surface flow rate of each sub basin was calculated by using Equation 7.4 and the average slopes of the stream existing in the basin were

calculated by extracting the elevation of the stream initial and end points from the DEM of the basin and the length of the stream is measured in Arc GIS 10.2.

The newly developed alternative sediment yield predication model was tested and evaluated by two methods: namely using model evaluation statistics between predicted and observed values and validated by applying on another sub-basin. Statistically, it was evaluated by using four widely used model evaluation 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)(Moriassi et al. 2007). To validate the applicability of newly developed model, one of the sub basin of Lake Ziway Katar was used. Lake Ziway has two tributary rivers (Maki and Katar) and for both of them, the daily river flow rate was available in MoWIE and the daily sediment flow rate was determined by using a sediment rating curve developed for the sites. Hence, the empirical model developed for sub basin Maki was checked inside of Karat sub-basin.

7.3. Results and discussion

7.3.1 Curve number of Lake Ziway basin

From a hydrological point of view, the rainfall runoff relationship allows one to infer the hydrological behaviors of a watershed. Figure 7.2 presents the rainfall-runoff relationship for the Lake Ziway Basin based on an analysis of the hydrological database of the year 2010.

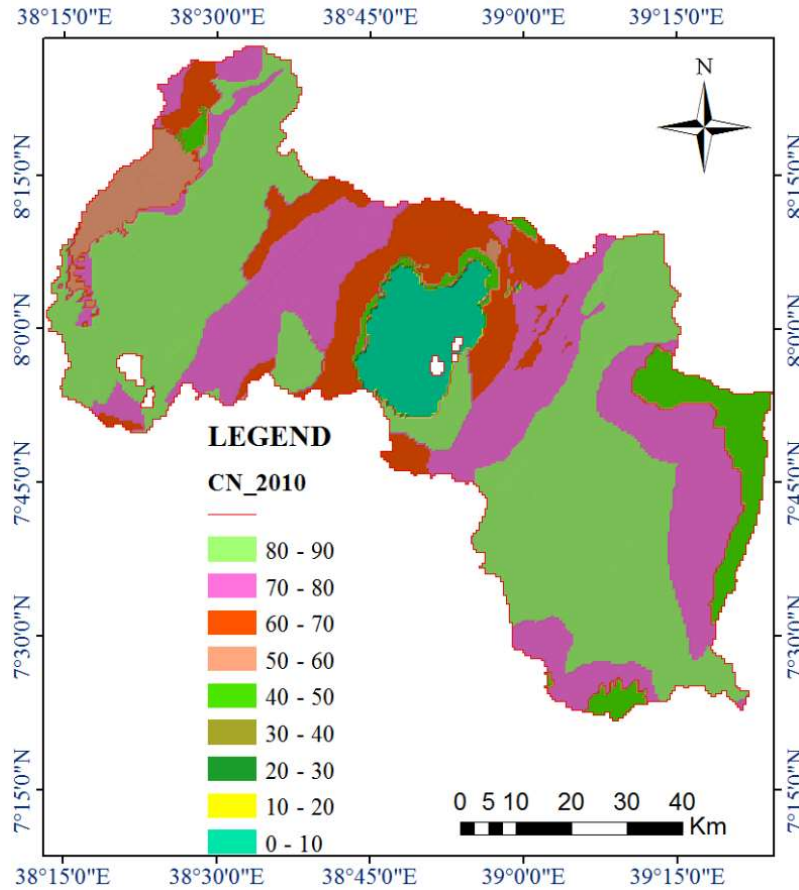


Figure 7. 2 Curve number (II) map for Lake Ziway Basin

7.3.2 Alternative sediment predication model

By using the none linear regression method, an alternative sediment yield predication model is established by DataFit version 9.0 model as:

$$SY = 0.04 (Q_s^b * A * S_b * K) + 0.07 (q_r^d * S_r) \quad (7.8)$$

where SY is sub basin sediment yield (tone/month), Q_s is Surface runoff (m^3/s), A is area of each sub basin (km^2), S_b is average slope of each sub basin (%), K is soil erodibility factors of the soil, q_r is stream flow (m^3/s) and S_r is average slope of the river (%).

In the model, b and d are peak flow adjustment factors. The value of b varies between 0.001 to 0.62144 with mean value of 0.31072 and, d varies between 1.284252 to 1.3983401 with mean value of 1.341296. The selection of flow adjustment factors d and d are similar with the selection criteria of curve number. As the curve number CNI is recommended for dry seasons, the value of minimum d and b will be employed in such conditions of the seasons. Like as the curve number CNIII will be employed during rainy seasons. The similar approach is accepted for flow adjustment factors b and d. Hence in wet seasons the value of b and d will be 0.62144 and 1.3983401 respectively. For other normal seasons, the mean value of b and d will be employed.

7.3.3. Evaluation of the newly developed model

7.3.3.1 Testing for Maki sub basin

As the curve number varies from year to year due to change in land use, a single curve number cannot be employed for more than three to four years. The land used land cover change study in Katar sub basin of Lake Ziway by [Tufa et al. \(2015\)](#) indicates as there is a significant land use changes in the past two and half decades. According to their study, the dominant land use change was agriculture with 27.7% between the year 1986 to 2010. As our curve number was developed for the year 2010, the evaluation of the model performance was employed only for three to four years before and after the year 2010.

The alternative model was developed in Maki sub basin by using geomorphological parameters of each 26 sub basins (Figure 7.1) and is tested for their common outlet point (Maki gauging station). For their common outlet point (gauging station Maki), the monthly

sediment yield determined by an alternative empirical model and observed on the gauging station is shown in Figure 7.3.

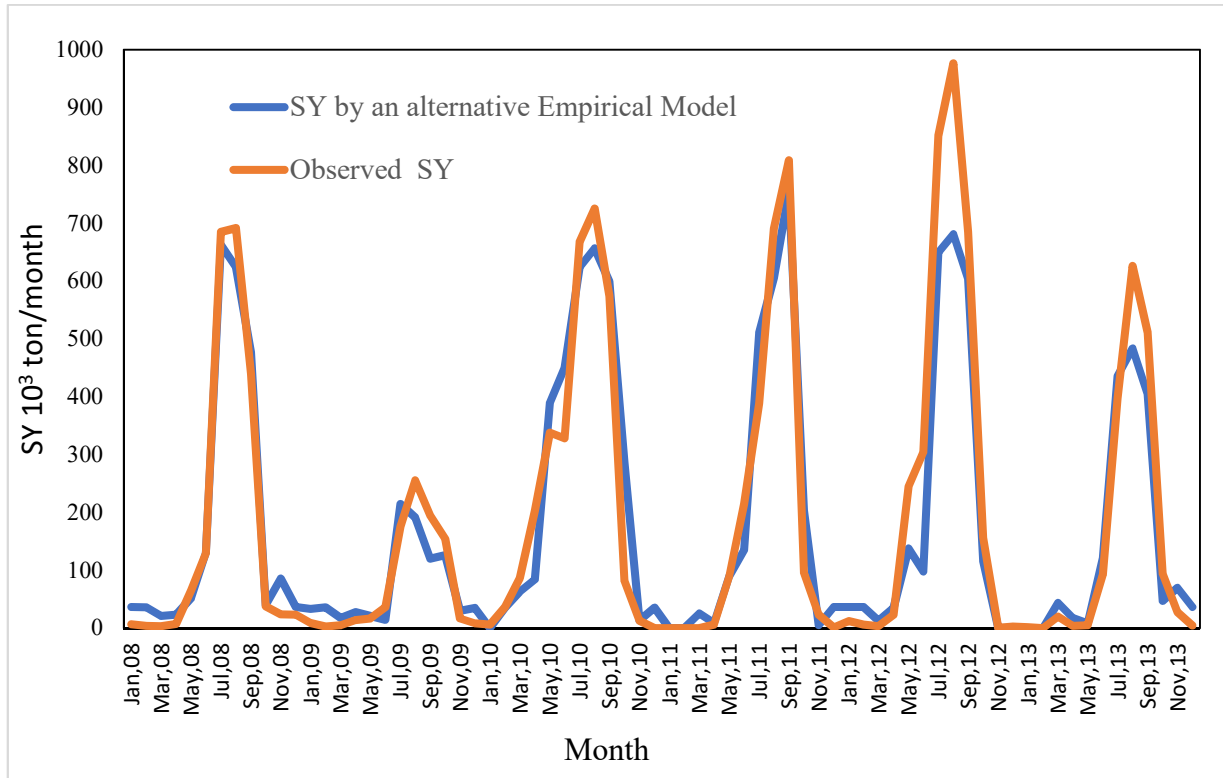


Figure 7. 3 Sediment yield determined by empirical model and observed on Maki gauging station

The time series plot of Figure 7.3 indicates that, the sediment yield observed and predicted by a newly developed alternative model matched well for both dry and wet seasons of the years. Similarly, the relation between the sediment flow rate determined by new empirical model and observe is shown in Figure 7.4 and well matches with each other.

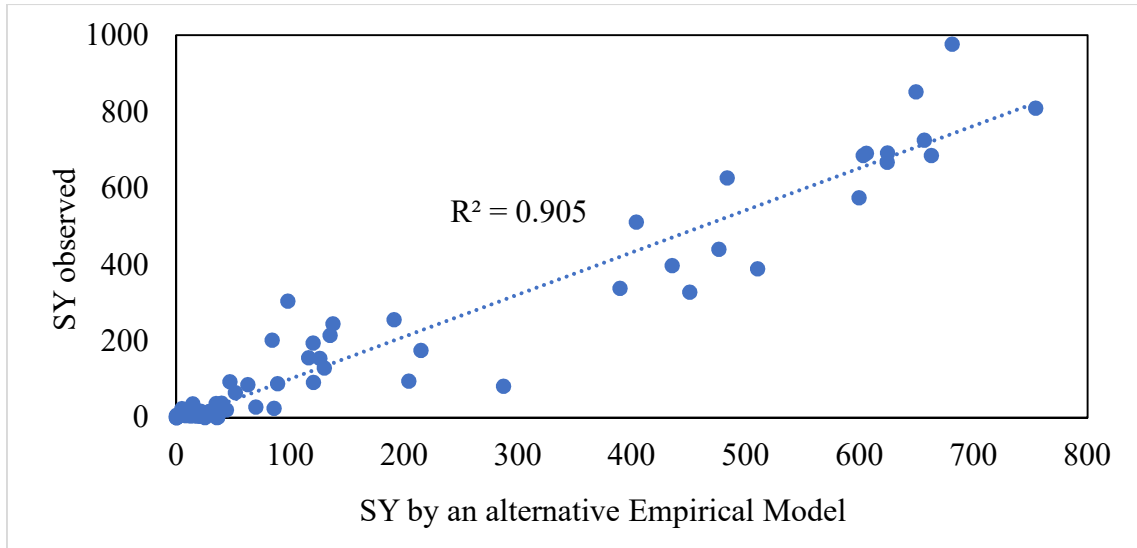


Figure 7. 4 The relationship between observed and predicated from newly developed model

As [Moriassi et al. \(2007\)](#) demonstrated, if the R^2 Value is > 0.9 , 0.9 to 0.75 , 0.65 to 0.75 and > 0.50 , the model can be rated as; excellent, very good, adequate and satisfactory performance, respectively. From Figure 7.4, it can be observed that the alternative sediment predication performance is excellent ($R^2=0.905$). Additional numerical criteria of model performance evaluators namely: NSE, RSR and PBIAS are determined and summarized in Table 7.3.

Table 7. 3 Statistics values for model performance

Statistics	R^2	NSE	RSR	PBIAS
Statistics values	0.905	0.89	0.32	4.98

As recommended by Reference ([Moriassi et al. 2007](#)), the high R^2 and NSE (above 0.9) values and the reasonably low RSR (below 0.5) and PBIAS (below 5) indicate the excellent correlation and agreement between developed alternative sediment estimation model and

observed one. As shown in table 7.3, for all statistical evaluators, the performance of newly developed model is excellent.

7.3.3.2 Evaluating the model performance inside of Kata sub basin

The Katar, one of the sub basin of Lake Ziway was used to evaluate the model performance. The sub basin has a drainage area of 3225 km² on stream gauging station of Abura (Figure 7.1) and the newly developed alternative sediment yield estimation model was tested to compute the sediment outflow from the basin. The computed monthly sediment yield determined by an alternative empirical model and observed on gauging station is shown in Figure 7.5.

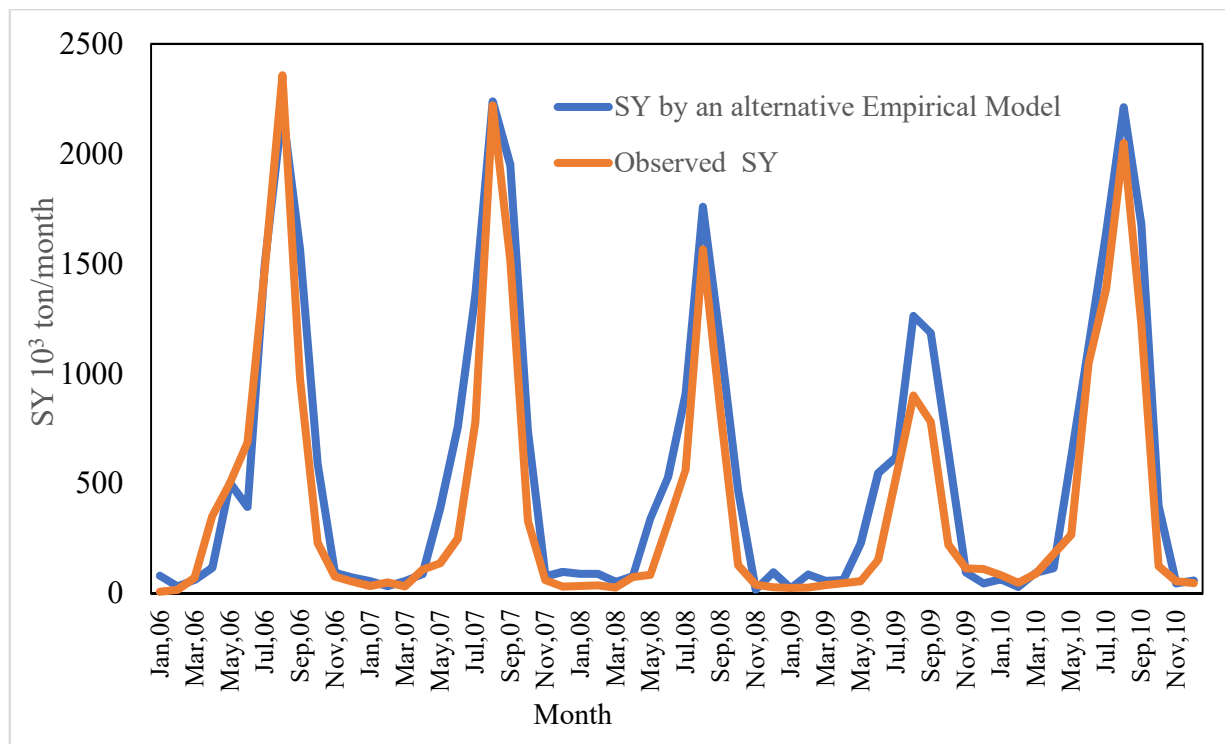


Figure 7. 5 Sediment yield determined by empirical model and observed on Katar Rive Abura gauging station

The time series plot (Figure 7.5), that indicated the ration between an observed monthly sediment concentration and that predicated in an alternative model indicates as it has well matched for both dry and wet seasons of the years. Similarly, the relation between the sediment flow rate determined by new empirical model and observed in the gauging station Abura is shown in Figure 7.6 and well matches with each other.

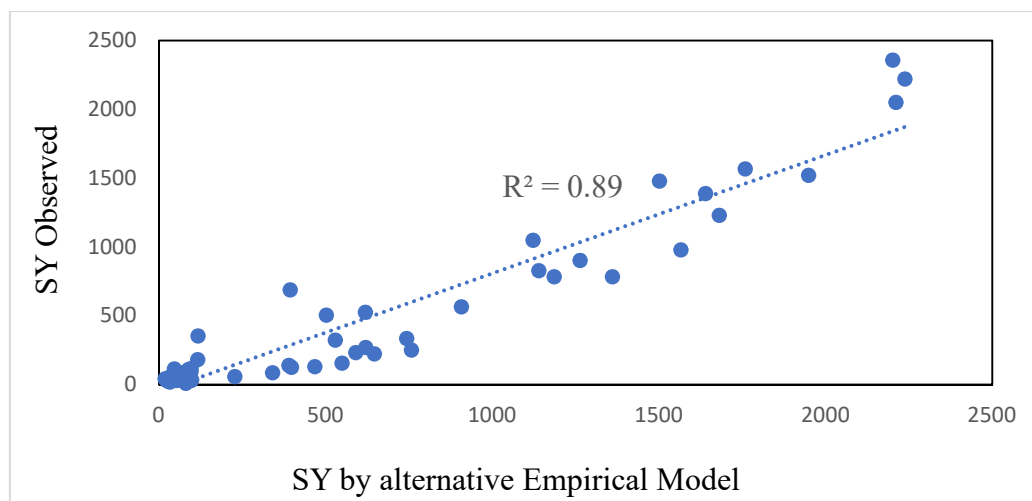


Figure 7. 6 The relation of observed and predicated SY on Katar gauging stations

Additional numerical criteria of model performance evaluators namely: NSE, RSR and PBIAS are determined and summarized in Table 7.4. As recommended by [Moriasi et al. \(2007\)](#), the high R^2 and NSE values and the reasonably low RSR and PBIAS indicate the excellent correlation and agreement between data generated by an alternative model and observed one. As shown in Table 7.4, the performance of newly developed model is very good to excellent.

Table 7. 4 Statistics values for model performance

Statistics	R^2	NSE	RSR	PBIAS
Statistics values	0.89	0.85	0.46	-30.28

7.3.4 Some of the unique difference of the newly developed model from the existing once

In soil erosion predication methods, the USLE has a long story. The modified of USLE was also derived by [Williams \(1975\)](#) and it be used to estimate sediment yield in a catchment. The MUSLE has been applied for sediment yield investigation in many parts of the world. Moreover, the equation has been used as a basis for the development of physically based models like SWAT ([Arnold et al. 1995](#)). This model has been popularly applied in many parts of the world for watershed sediment yield modeling. Here, the newly developed model has some similarity with USLE model. Like to that of USLE, it accounts the effect of rain fall, soil, land use and slopes of the watershed. Unlike to that of USLE model, it accounts the impacts of stream flow conditions on sediment transportation. Both the detachment and transport limited forms of erosion can be assessed in this method.

In northern Ethiopia, [Tamene et al.\(2006\)](#) were developed the model that can estimate the sediment yield of the watershed. The developed mode by [Tamene et al. \(2006\)](#) is shown as:

$$\text{LogSY} = 0.007 * \text{SBCG} + 0.003 * \text{ELL} + 0.002 * \text{RG} - 0.007 * \text{BUSH} + 2.33 \quad (7.9)$$

where, Log SY is sediment yield in $\text{t km}^{-2} \text{ yr}^{-1}$, SBCG is standard bank collapse and gully erosion, EL is proportion of erodibility lithology in %, RG is surface roughness and BUSH is proportion of bush or shrub cover in percentage.

As shown in equation 7.9, the effect of climate parameters was not explicitly included. As indicated in USLE and on its derivatives, climate is one of the major factors that govern the watershed sediment flow. In the discussion parts of the investigation, [Tamene et al. \(2006\)](#) pointed out the need for further analysis to obtain a good sediment predication model by

incorporating climatic factors of the watershed. Hence, this study may answer the down back seen on previous studies.

7.4 Conclusions

The newly developed an alternative watershed sediment yield estimation model was developed by using the geomorphologic, hydrologic and hydraulic parameters of the watershed. It was developed based with an assumption that the sediment delivered on the outlet of the basin is originated from the upland area of the basin and from the section of stream channel. Basin area, slope, soil erodibility rate and surface runoff were used as a component that govern the sediment yield on uplands of the basin. Similarly, stream channel slope and rate of stream flow was taken as component that govern the sediment yield instream.

An alternative sediment predication model was developed in side of Maki sub basin of Lake Ziway and its performance was tested by using the commonly used model evaluation 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). The applicability of the model for other basin was also tested by using Katar sub basin as a case study. Hence its applicability was validated in Katar sub basin. Statistically, the performance of the model inside of Maki sub basin is excellent, and during validation, the newly developed model performance is excellent to very good.

The model was also tested by plotting the time-series graphs of sediment estimated by newly developed model and measured one. The result indicates that an alternative model is

duplicating the sediment yield measured in the gauging stations. To apply a physical based model like SWAT, the main factor hindering it is the lack of measured sediment data. For the study area, the developed model is a solution for such problems. Lastly, we would like to recommend to test the applicability of newly developed model in other basins of the world and based with such results it can be incorporate with SWAT SUFI-2 program to calibrate the sediment yield for data scared area.

8. CONCLUSION AND RECOMMENDATIONS

The main objective of this study is to model the sediment yield, transport and deposition in Lake Ziway Basin. Despite the complexity of processes influencing sediment yield and deposition in the basin, this research demonstrates three different approaches for predication; 1) Direct measurements of sediment in the river; 2) Multi-frequency reservoir survey; and 3) Physically based models, specifically the SWAT model.

The suspended sediment concentration of the rivers discharging into Lake Ziway is measured for both dry and wet periods at gauging stations located upstream and downstream of each flood plain to determine sediment lost in the flood plains of the rivers. Sediment transport rates are estimated from rating curves developed with normal-linear log-log regression, normal log-log regression and non-linear log-log regression methods. As a result, the gross annual sediment yield discharged into the lake is 2.081Mt. Annually, 0.178Mt sediment is deposited in the floodplains with sediment trapping rate of 20.6%. An amount of 41,340 tone/year of sediment leaves the lake through Bulbula River. The annual sediment deposition rate in the lake is 2.039Mt with a mean sediment-trapping-efficiency of 98%. Based on the established sediment budget with average rainfall, the lake will lose its depth by 3.98mm and its volume by 0.106% per year.

The sediment deposition pattern and its rates inside the lake surface are determined by comparing the two bathymetry maps from data taken in 2005 and 2017. The quantity of sediment deposited in twelve years, between the bathymetry dates, is estimated to be 17.75 MCM. This has resulted in 1.12% loss of the lake capacity. Assuming a constant rate over the

period, the annual sedimentation is 1.479 MCM. By taking an average bulk density of 1.22 ton/m³ for the basin soil the annual sediment yield and the annual reduction in storage capacity are estimated to be 1.81Mt and 0.093%, respectively. This result compared with lake sediment budget determined from sediment flux of tributary rivers, slightly under estimates the lake sediment deposition rate. However, the difference between the sediment deposition rates estimated by both methods is below 9% and both estimates are acceptable. Based on the above deposition rates, half-life of the lake will be 474 to 520 years.

The goal of erosion and sedimentation study is to control its ill effect on both catchment and water body. To develop sound sediment management plans, prioritizing watersheds by soil erosion severity and risk indices is essential. The physically based model (SWAT) was used to delineate the areas in the basin which are in high erosion risk. SWAT model is calibrated by applying SUFI-2 program and the performance of the model is assessed. The catchment prioritization study indicated that some sub-basins having the same soil type and landuse but a higher slope give higher sediment yield. This confirms that the upland of the basin is the main source of sediment for the lake hence the variation of sediment yield is more sensitive to terrain slope. Furthermore, the soil conservation scenarios demonstrated in SWAT that for watershed slopes greater than 5%, reducing the slope length by 50% decreases the sediment yield of the basin by 55%. Hence, this result can be used as input for organizations and decision-makers to apply a suitable method to reduce the erosion intensity especially at hot spots.

In studying the sediment yield of the basin by physical or mathematical models, the soil susceptibility for erosion is an initial index. In this study, an alternative soil erodibility

estimation factor (KET) is developed by mimicking and minimizing the data required in Sharply and Williams (1990) soil erodibility index values that are put in EPIC (Erosion productivity impact calculator). The similarity of results obtained using KET is compared with the results of EPIC-K by using model performance statistics. The performance of KET is found to be excellent for predicting the erodibility of soils of Ethiopian Rift Valley Lakes Basin. For 35.7% of the soils in Ethiopia, it predicts erodibility within $\pm 5\%$ relative error. The alternative erodibility equation can be applied for soils across Ethiopia with a relative error and standard deviation of -9.88% and 6.4, respectively. By applying KET, the K map for ERVLB and Ethiopia is produced. The soil erodibility map developed for ERVLB is validated using field data and it is recommended to use it with confidence.

Suspend sediment load or total sediment load prediction formulas are developed and used around the world. Most of them are based on laboratory results and their applicability is in question. In this study, an empirical model is developed using the hydro-geomorphology and stream flow characteristics of the basin to estimate the sediment yields of the watershed. It is tested for its applicability using model evaluation statistics. Furthermore, its applicability is validated by testing in other sub-basins of the lake. Validation showed that performance of the model is statistically acceptable. Hence, it is recommended to test the applicability of a newly developed model in basins other than the basin where it is developed and incorporate it with SWAT SUFI-2 program to calibrate the sediment yield for data scarce areas.

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