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Estimating reservoir sedimentation using bathymetric differencing and hydrologic modeling in data scarce Koga watershed, Upper Blue Nile, Ethiopia

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Abstract: Modeling sediment accumulation in constructed reservoirs is hampered by lack of historic sediment concentration data in developing countries. Existing models simulate sedimentconcentration using data generated from sediment rating curves usually defined as a power function of the form $S = aQ^b$. This often results in residual errors that are not identically distributed throughout the range of stream flow values adding to uncertainty in sediment modeling practices. This research measure accumulated sediment in Koga dam in the upper Blue Nile Basin and use the result to validate a Soil and Water Assessment Tool (SWAT) sediment model that uses sediment data from rating curves. Bathymetric differencing of the original and current storage digital elevation models (DEMs) indicate that the sediment was accumulating at a rate of 5 ton/ha/year while a calibrated SWAT model resulted in 8.6 ton/ha/year. Given the complicated sediment transport processes that are not fully understood and comparable rates reported in recent studies these results are satisfactory.

Keywords: reservoir sedimentation, Koga reservoir, bathymetry

Introduction

Problems of sediment accumulation in reservoirs built on natural beds have been a major storage capacity detriment (Almeida *et al.*, 2005). Sediment deposition in irrigation canals, stream channels, reservoirs, water conveyance structures, reduces their capacity and would require costly operation for removal (El-Swaify, 1994). Worldwide costs of soil erosion in 1995 were estimated to be about four hundred billion dollars per year (Pimentel *et al.*, 1995).

Human activities such as watershed management practices (WMP) modify landscapes that influence runoff and sediment delivery (Yan *et al.*, 2014). In areas where land use did not change significantly after a reservoir was built exceptionally high rainfall are reported to be major drivers of reservoir sedimentation (Dong *et al.*, 2013).

Scour, transportation, and deposition of sediments are complicated processes. A number of models have been developed to estimate this process (Jetten *et al.*, 2003; Jordan *et al.*, 2005; Rompaey *et al.*, 2005). Earlier models include the universal soil loss equation (USLE) (Wischmeier, 1959) and erosion productivity impact calculator (EPIC) (Williams, 1983). The SWAT model calculates sediment from a hydrologic response unit (HRU) using the Modified Universal Equations (MUSLE) which depends on the rainfall runoff energy to entrain and transport sediment (Williams and Singh, 1995). Detailed description of the SWAT is provided on literatures (Arnold *et al.*, 2007; Neitsch *et al.*, 2005).

There is an existing knowledge base with respect to the stream discharge and sediment modeling (Chebud and Melesse, 2009a, b; Conway, 2000; Dile *et al.*, 2013; Kebede *et al.*, 2011; Kebede *et al.*, 2006; Setegn *et al.*, 2011; Setegn *et al.*, 2008; Setegn *et al.*, 2010; Tarekegn and Tadege, 2006; Wale *et al.*, 2009; White *et al.*, 2011; Yasir *et al.*, 2014) using SWAT. Improved hydrologic models have also been more successful in predicting runoff (Easton *et al.*, 2008; Steenhuis *et al.*, 2009; Tilahun *et al.*, 2012). Nevertheless all of these models derive the sediment data from a sediment rating curve of the form $S = aQ^b$ where S is sediment concentration in mg-1, Q is the rate of flow in m^3 per second and a and b are site specific parameters. A power rating curve used in the case of Koga river with parameter value of 7.47 and 1.821 for a and b (R2=0.913) respectively. Parameter estimates obtained for the non-linear model do not require a correction for transformation bias. However, the residual errors of the non-linear model typically are not identically distributed throughout the range of stream flow values (Crawford, 1991). This problem adversely affects the precision of the parameter estimates and hence the sediment data quality. Sediment rating curves are also established based on a single point random time grab samples and are inherently biased in representing all range of flows i.e. the rating curve that has been used in this research is based on samples only in the wetting season which doesn't include the low flows in the dry period. Harmel *et al.* (2006) noted that the uncertainty in using manual single point random time grab sampling could be in excess of 50% and -5.3–4.4% due to the method used in sample analysis. Model parameters using these data are thus subject to greater uncertainty and are less reliable in understanding the sedimentation process.

Constructed reservoirs provide the opportunity of comparing storage characteristics variations as the reservoir topography during construction and after some time of storage can easily be compared using GIS techniques. This helps to overcome the uncertainty in historic sediment data generated using sediment rating curves. In this study we measure accumulated sediment in a dam using DEM differencing and compare the result with a modeled sediment inflow to the Koga reservoir in Ethiopia. The approach can be applied to validate sediment model parameters in the data scarce upper Blue Nile basin where a massive dam building activity is currently taking place.

Material and methods

Study area

The study was conducted at Koga irrigation dam, near Bahir Dar, Ethiopia (11°10' N, 37° 02' E). The impoundment is an instream system formed by the damming of Koga river, a second order stream (Figure 1) flowing to Lake Tana. The Koga River that drains the 250 km^2 watershed is a tributary of the Gilgel Abay River in the headwaters of the Blue Nile basin which flows into Lake Tana. The average discharge based on 44 years of record (1959-2002) is 4.78 m^3 per second. With elevation between 1,900 to 3,200 meters the watershed is subject to the inter-tropical convergence zone and a single rainy season that begins in June and lasts through September resulting in 70% of the river flow. The high rainfall variability renders high vulnerability amongst small-scale farmers who rely on rain-fed agriculture. Koga River minimum flow occurs in April and May, just before the onset of the rainy season. Major forms of land-use/land cover include cultivated land (54%), forest (10%) and grassland (8%). Dominant soil types include Haplic Alisols (38%), Haplic Luvisols (24%) and Eutric Vertisols (20%). The most important environmental problems observed in the area are soil erosion, deforestation, and poor land use and management. The rate of soil loss in the furthest upstream portions of the watershed exceeds the soil formation rate, in part because of the severe deforestation in the 1970s and 1980s (Tilahun 2009).

Koga reservoir has a storage capacity of 83.1×106 m^3 of water and inundates 18.56km^2 at full supply level. The reservoir provides water to irrigate 7,000ha owned by 5,000 households. Stream flow was monitored at Ministry of water, irrigation and electricity (MoWIE) gauging station (11°25'16.0"N, 37°09'48.8"E) 3.5 km downstream of the reservoir. Mean daily discharge averages 4.78m^3 per second (1959–2002), with the highest and lowest average flows recorded in July and April, respectively. The most important environmental problems observed in the area are soil erosion, deforestation, and poor land use and management. The rate of soil loss in the furthest upstream portions of the watershed exceeds the soil formation rate, in part because of the severe deforestation in the 1970s and 1980s.

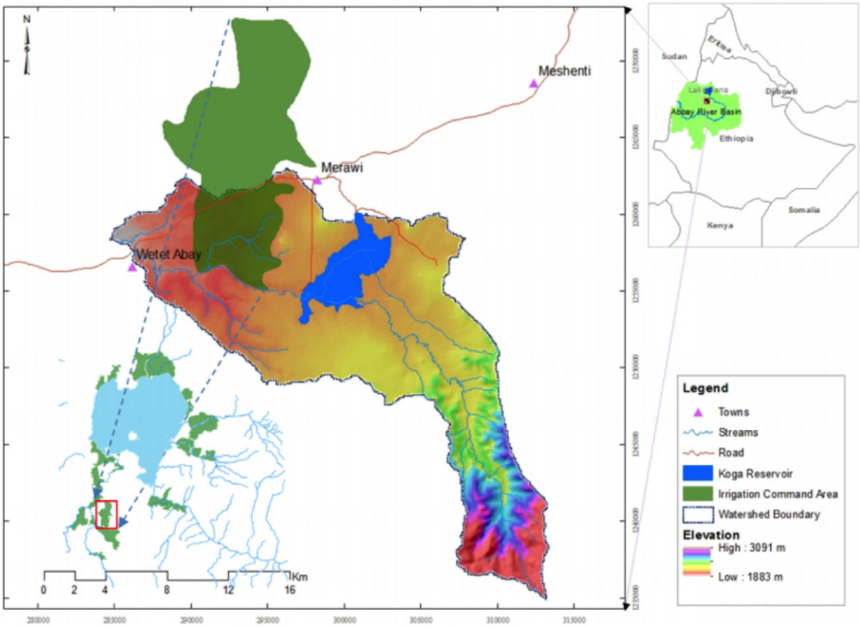


Figure 1 - The Koga watershed, reservoir and irrigation extent. The inset map shows the Koga irrigation scheme in the Tana sub basin

Bathymetric surface generation

Reservoir systems offer the advantage of pre filling topographic data and other associated data related to the operation of the reservoir. These advantages can be exploited to understand the sedimentation process in the watershed. We used two sets of reservoir topography map; one produced for the construction of Koga dam and the other collected in 2013 bathymetric survey. The CAD layer for the original topo map is converted to a GIS layer and interpolated to a DEM. The 2012 bathymetry was conducted using a single beam echo-sounder. A total of 3,087 points are collected in a regular grid on average of 35 by 35 meters. Survey lines consisted of north-south and east-west transects. The total track-line distance of the survey was approximately 500km (Legesse, 2012). The depth measurements are converted to a GIS layer for analysis. An exploratory data analysis is carried out to remove outliers and examine the distribution of the depth readings. About 3,000 depth measurements are used to generate a DEM. The 'Topo to Raster' tool in ArcGIS is implemented in creating both DEMs to avoid uncertainty in applying different approaches. Given the small size of the reservoir area and the accuracy required a TIN-based analysis is preferred and hence the DEMs are converted to a TIN. TINs are typically used for high-precision modeling of smaller areas, such as in engineering applications, where they are useful because they allow calculations of surface area, and volume.

The DEM difference gives a measure of accumulated sediment in the last four years and is used to calculate the aerial average annual sediment contribution rate of the Koga watershed. The volume of successive polygon has been determined by calculating the difference in height between measurements of the two input surfaces. First surface is the bathymetric surface from which the second (digitized topographic surface) or reference surface has been subtracted.

SWAT modeling

Detailed description of the SWAT is provided on literatures (Arnold *et al.*, 2007; Neitsch *et al.*, 2005). The runoff is estimated separately for each Hydrologic response units (HRUs) and routed to obtain the total runoff for the watershed. HRUs are lumped land areas within the sub-basin that comprised of unique land cover, soil and management combinations. The water balance in an HRU is simulated by SWAT using the following equation.

$$SW_t = SW_o + \Sigma_{i=1}^{n} (R_{day} - Q_{surf} - E_{\alpha} - W_{seep} - Q_{gw}) \quad (1)$$

Where:
-SW_t and SW_o are final and initial soil water content at time t and to in mm respectively,
-day is precipitation on day i in mm,
-Q_{surf} is surface runoff on day i in mm,
-E_a is evapotranspiration on day i in mm
-w_{seep} is percolation on day i in mm and
-Q_{gw} is return flow on day i in mm.

Sediment transport processes are simulated via soil erosion and sediment transport from the hill slopes of the catchment and the sediment processes in the stream channel (Neitsch *et al.*, 2005). The sediment yield from a HRU is calculated using the Modified Universal Equations (MUSLE) which depends on the rainfall runoff energy to entrain and transport sediment (Williams and Singh, 1995):

$$Sed = 11.8\ (Q_{surf} \cdot q_{peak} \cdot area_{hru})\ 0.56 \cdot K_{USLE} C_{USLE} P_{USLE} LS_{USLE} \cdot CFRG \quad (2)$$

Where
- Sed is the sediment yield on a given day (metric ton),
- Q_{surf} is surface runoff volume (H_2O/ha),
- q_{peak} is peak runoff rate (m^3/s),
- $area_{hru}$ is area of HRU (ha),
- K_{USLE} is the soil - erodibility factor (0.013 metric ton m^2hr/(m^3-metric ton cm)),

- C_{USLE} is the cover and management factor,
- P_{USLE} is the support practice factor,
- L_{SUSLE} is the topographic factor and
- CFRG is the coarse fragment factor.

More detailed descriptions of the model can be found in Neitsche *et al.* (2005). The model setup involved five steps: data preparation, sub-basin discretization and HRU definition, sensitivity analysis, calibration and validation. The spatial data required in SWAT are the Digital Elevation Model (DEM), soil, and land use data. A 30 m by 30 m resolution DEM is used to delineate the watershed, analyze the drainage patterns of the land surface terrain and generate the topographic wetness index. Sub-basin parameters are derived from the DEM. The soil data is acquired from the new Harmonized World Soil Database (HWSD) (Nachtergaele *et al.*, 2008). The land use map was obtained from the Abay Basin master plan document (BCEOM, 1999). The weather variables data were obtained from Ethiopian National Meteorological Agency (NMA) for the nearest Bahir Dar station. In order to fill gaps in some of the data the weather generator file created by White *et al.* (2011) was used. Daily discharge data is available for 1993 – 2006 period. Stream flow data is not available from 2006 onwards which leads to a major assumption that erosion processes and rates are stable over a shorter period of time. Given the almost nonexistent land cover change in the area this assumption is justifiable. The sediment data is generated using sediment-discharge rating curve (R=0.913) developed by MOWIE for long term discharge data.

SWAT calibration uncertainty programs (SWAT–CUP), SWAT-CUP is an interface that was developed for optimizing the SWAT output linked to ArcSWAT to calibrate the model and perform uncertainty analysis. SWAT is physically based, uses readily available inputs, is computationally efficient, and is a continuous model that operates on a daily time step. In SWAT, the entire watershed can be divided into several sub basins and each sub basin is further divided into unique combinations of land use and soil properties called the Hydrologic Response Unit (HRU). The SWAT–CUP program includes five calibration routines (SUFI–2, ParaSol, GLUE, MCMC and PSO). Previous detailed studies had shown sequential uncertainty fitting (SUFI–2) program performs better for Gumera watershed (Setegn *et al.*, 2008). A t-test is then used to rank parameters and identify the relative significance of each parameter. Calibration of daily flow and sediment was performed from 1995–2002 with the first year as a warm up period and the validation period was 2003–2006. The water balance was calibrated first followed by the sediment obtained from rating curve.

The model parameters are checked for maintaining their physical meaning (i.e. whether they are within the specified limits). The performance of the simulation was evaluated using the Nash– Sutcliffe coefficient of efficiency (NSE) (Nash and Sutcliffe, 1970). The NSE is computed as:

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n} (Q_{i,s} - Q_{i,m})^2}{\sum_{i=1}^{n} (Q_{i,s} - \bar{Q}_m)^2} \qquad (3)$$

Where:

$Q_{i,s}$ is simulated quantity (flow or TSS),

$Q_{i,m}$ is measured quantity and

mm is mean of the measured quantity.

The sediment inflow rate from the SWAT model is then aggregated to annual sediment volume for comparison with the sediment volume computed using DEM differencing. The workflow diagram (Figure 2) summarizes the procedure followed in this study.

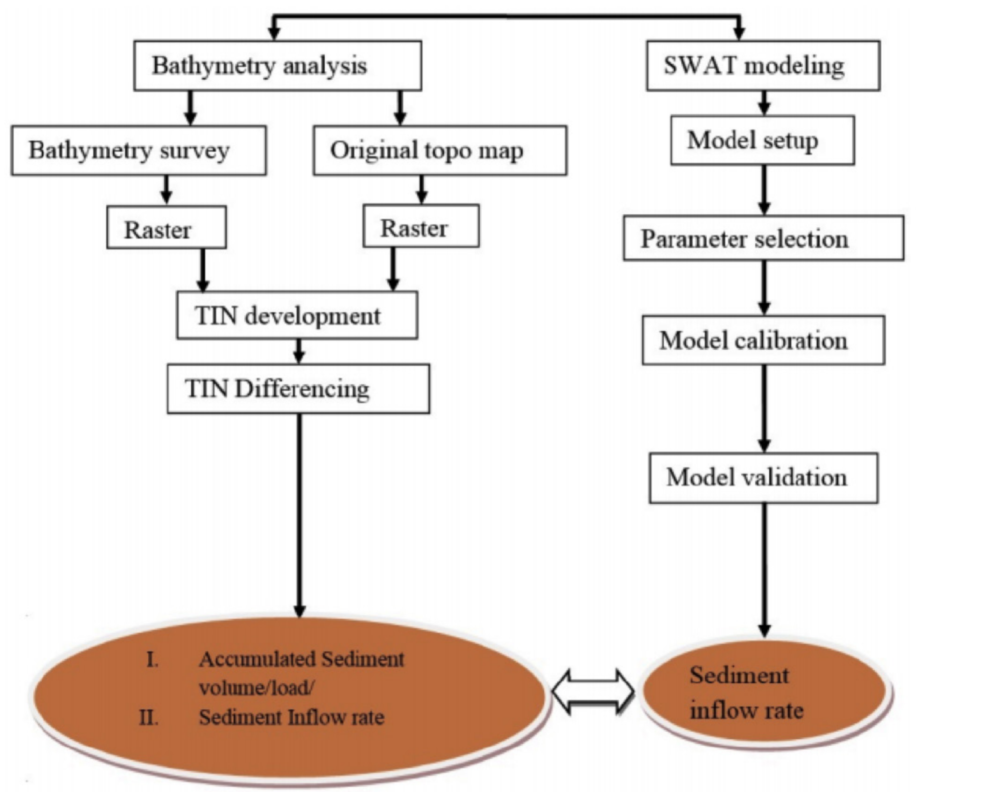


Figure 2 - Work flow diagram

Results and discussion

Sedimentation estimate using DEM differencing

The sediment accumulation (Figure 3) in the reservoir is obtained as the difference between the TIN derived from the topographic map and the TIN derived from the bathymetric survey the result showed that the storage volume shrunk from its design storage of 83.1 Mm^3 in 2009 to 82.7 Mm^3 in 2012, i.e., sediment inflow volume of 339,500m^3.

Annual average sediment inflow rate was 84,800m^3. Taking the average density of clay soil of 1.2tons/m^3 annual sediment yield is estimated to be 101,500 ton/year or (500tons/km^2/year). The dead storage for Koga reservoir is 393,000 m^3 (MacDonald, 2004). Based on the annual sediment inflow rate of 84,800m^3 obtained through DEM differencing the dead storage is about 4.6 years of sediment accumulation and

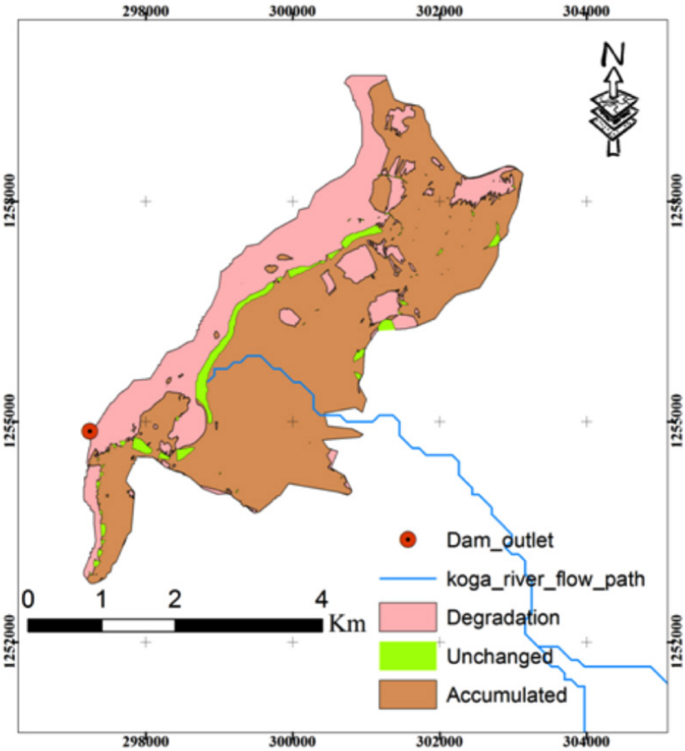


Figure 3 - Sediment distribution in Koga reservoir with sediment extents with reference to the original topography

represents the loss of 0.4% of the total storage of the reservoir.

However, this does not mean that the dead storage will be filled with sediment after a period of 4.6 years, as two factors must be taken into account. The first is that siltation in the reservoir will not be at a uniform level, due to a greater deposition expected further upstream within the reservoir, as much of the silt will begin to settle out where the flow is first slowed. This will depend on the actual reservoir level, when floods carrying a significant silt load occur. The bathymetric survey also indicated that much of the siltation occurred around the middle portion of the reservoir. Second, the reservoir has a combined irrigation draw off and bottom outlet works in a single Intake Tower which enables the latter to be utilized to flush any silt deposited in front of the Irrigation Intake (i.e. near the dam body). As the result the DEM differencing operation shows deposition at the periphery of the reservoir and erosion in front of the irrigation intake.

Sediment accumulation using SWAT model

Out of the thirteen SWAT parameters employed in the calibration (Neitsch,2005) threshold depth for water in shallow aquifer (GWQMN) is clearly identified as a sensitive parameter followed by soil bulk density (SOL_BD) and effective hydraulic conductivity in main channel (CH_K2) for the sediment component (Table 1)

The observed and simulated flows for calibration and validation periods are provided in figure 4(a) and (b). Observed and modeled sediment are shown in figures 5(a) and (b). The NSE for flow calibration (1995 – 2002) and validation (2003 -2006) were 0.53 and 0.5 with R^2 values of 0.66 and 0.61 for the calibration and validation periods respectively (Table 2). The model performance indicators revealed that the SWAT model can satisfactorily predict the long term sediment catchment yield of

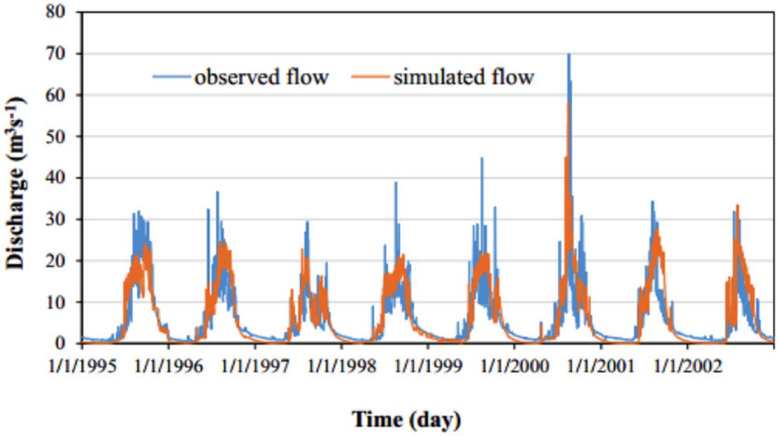
Table 1 - Sensitivity analysis results

Parameter	t-stat	p-value	Lower bound	Upper bound	Fitted value	Rank
GWQMN	0.8	0.50	0	5	3	1
SOL_BD	0.77	0.51	0.9	2.5	1.54	2
CH_K2	0.74	0.53	30	450	225	3

Table 2 - Summary of SWAT model performance in simulating sediment load for Koga catchment

Variable	Period	Performance indicator	
		NS_E	R^2
Runoff	Calibration	0.53	0.66
	Validation	0.50	0.63
Sediment	Calibration	0.52	0.64
	Validation	0.50	0.60

the Koga watershed. The total sediment load carried by the Kogariver is estimated to be 90 ton/ha over eight years and its mean annual sediment inflow is obtained as 175,000 tons. The annual sediment load by SWAT is thus 860 tons/km^2 or 8.6 ton/ha/year. This is a slight over estimation as compared to the bathymetry analysis which is due to the fact that the observed data is obtained based on the rating curve equation for the long term flow and the algorithms of the methods are different. However Hurni (1986) found that in Ethiopian highlands the range of tolerable soil loss level for various agro-ecological zone of is from 2 to 18 tons/ha/year (200 to 1,800 tons/km^2/year). Other studies also suggested average sediment yield within the estimated



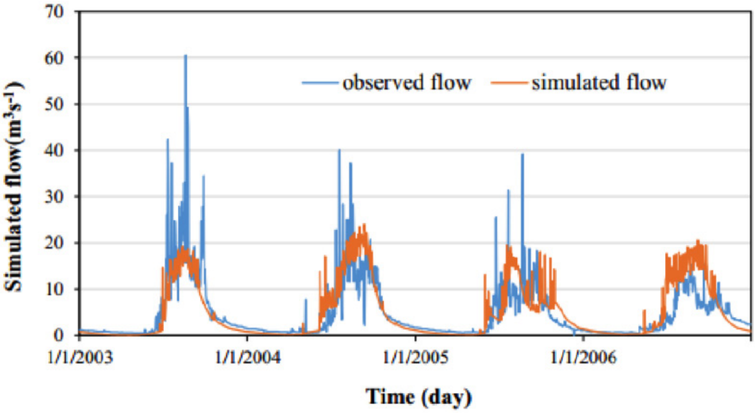


Figure 4 - Daily simulated flow and observed during (a) calibration (1995 – 2002) and (b) validation (2003 – 2006) periods

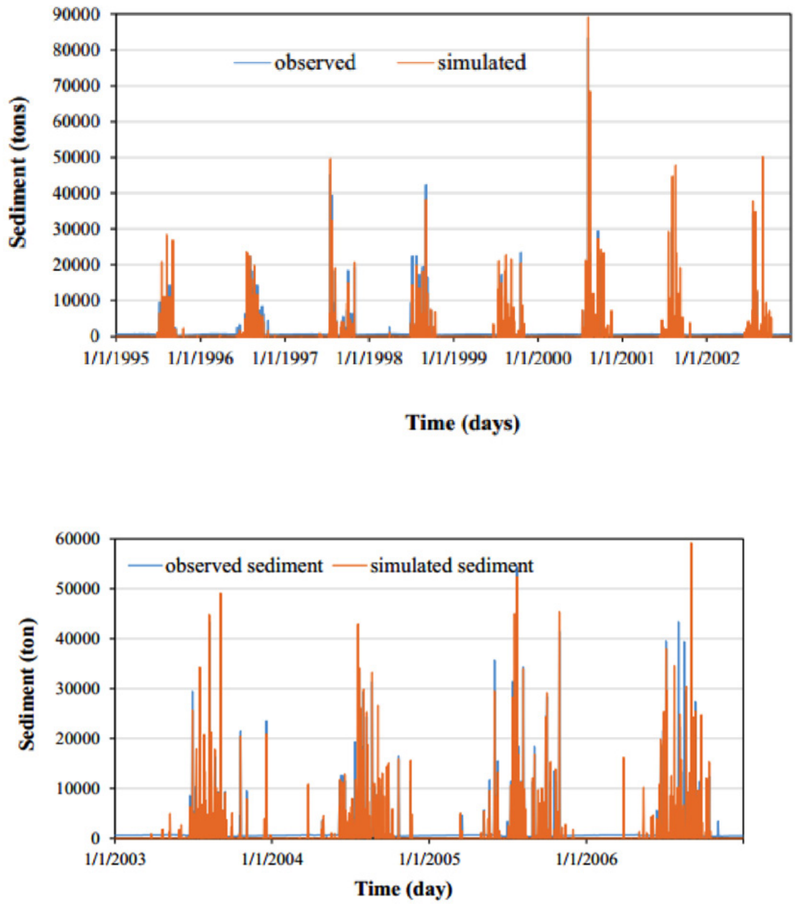


Figure 5 - Model output (a) calibration and (b) validation periods

ranges of this study (Hawando, 1997; Hurni, 1988; Tebebu *et al.*, 2010).

Conclusion

This study estimates sediment using the SWAT model and a DEM differencing technique in the Koga Dam basin. This study is a first attempt to quantify sediment accumulation in dams built in upper Blue Nile basin and provides important lessons for the several water impoundment projects underway and planned in the near future. The findings examine the suitability of sediment time series data often used in SWAT modeling. Our results showed that sediment time series data generated using traditional sediment rating curves generally leads to an over estimation. This is mainly due to varying accuracy of the rating curves at low and high flows. This means residual errors of the non-linear model typically are not identically distributed throughout the range of stream flow values. Sediment rating curve should thus be developed for the dry and wet season separately. The uncertainty in using manual single point random time grab sampling when establishing these rating curves are also major sources of error. On the other hand the SWAT model employed in this study lacks the mechanism to incorporate reservoirs thus do not account for sediment leaving the reservoir. Flushing, flow to irrigation plots and the release to maintain minimum ecological flow are all potential escape paths for sediment. Thus it is reasonable to expect slightly higher estimates with the SWAT model compared to the DEM differencing technique as can be seen in this study. Future studies should quantify and incorporate sediment outflow during flushing, flow to irrigation plots and releases through the outlet. Incorporating that sediment outflow to the SWAT model will certainly narrow the sediment budget gap and thus results in better estimates. The accuracy of the SWAT model helps in adopting the sediment process parameters to be used in the study of effect of soil and water conservation works on reservoir sedimentation in the future. Given the complicated sediment transport processes that are not fully understood in constructing the sediment time series it can be concluded that the results obtained are modest.

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