

SEDIMENT MANAGEMENT IN IRRIGATION RESERVOIR (CASE OF GIDABODAM)

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Abstract

Reservoir sedimentation is a gradual accumulation of the incoming sediment load from a river; it is important to predict sediment inflow at Gidabo Dam and evaluate its consequences on the reservoir. The overall goal of this study focuses on predicting sediment yield and its sustainability and identification of most appropriate sediment management strategy are under the scope of this study by applying SWAT model interface with GIS, Gidabo Dam Reservoir is the major. The model is calibrated and validated taking the Aposto station found in the catchment by transferring the gagged data to the outlet of Gidabo Dam. The model is calibrated and validated for both flow and sediment concentration at Aposto station (646km²) and run at Gidabo Dam Reservoir outlet (2532km²) to estimate the sediment yield. Flow calibration gives coefficient of determination (R²) and Nash-Sutcliffe simulation efficiency (ENS) 0.78 and 0.77 respectively. Flow validation gives 0.54 and 0.53 for R² and ENS values respectively. Sediment calibration gives R² and ENS 0.69 and 0.68 respectively and validation test gives R² and ENS 0.66 and 0.58 respectively. This result indicates that the observed values show good agreement with simulated value for both flow and sediment yield.

In this study the SWAT model yields average annual sediment of 66.215 ton/km²/yr or (6621.5ton/ha/yr) at Gidabo Dam outlet dam site.

Identifying erosion prone areas in the watershed enables the watershed management to be applied to the proper areas to reduce the sediment yield.

Key words:

Arcs SWAT, sediment Yield, flow simulation, calibration, validation, SWAT CUP.

1. INTRODUCTION

1.1 Background

Reservoir sedimentation is a gradual accumulation of the incoming sediment load from a river. This accumulation is a serious problem in many parts of the world and has severe consequences on water management, flood control and production of energy. In the present Situation, the worldwide loss of storage capacity in surface water reservoirs due to Sedimentation is higher than the increase in storage volume achieved through construction of new reservoirs (White, 2010). The worldwide loss in reservoir storage capacity is estimated to be between 0.5% and 1% per annum (Mahmood, 1987; White, 2010).

Soil erosion is the detachment and transportation of soil particles from their original place to further downstream by erosion agents such as water and wind. The severity of erosion increases with the decrease in cover material most likely vegetation. The vegetation cover decreases the soil erosion by decreasing the impact of raindrops that cause the detachment of the soil particles. Therefore, bare soil is more likely to be eroded by different soil erosion agents than soil with vegetation cover.

Soil erosion is a serious problem affecting the quality of soil, land, water resources upon which man depends for his sustenance. Today, soil erosion is universally recognized as a major environmental and agricultural problem, because as the top soil is eroded by erosion agents such as water, wind, avalanches, etc. its fertility and nutrient content decreases. This eventually results in the loss of reservoir productivity. (Verity and Anderson, 1990).

Reservoirs have to be considered as irreplaceable resources and have to be managed in accordance with the objective of sustainable utilization. Sediment production of a watershed is highly influenced by weathering effects caused by climatic factors like temperature variation, action of rain and chemical action from elements contained in the soil and water (ASCE, 1975).

Since the velocity of water in the reservoir is very low, sediments get deposited in the reservoir unless there exists a facility to avoid the settlement. The sedimentation of reservoirs causes another serious problem by decreasing the capacity of reservoirs. The loss in capacity of hydropower reservoirs increases the probability of floods. As more and more sediments get deposited in the reservoirs, its capacity decreases and ultimately will not be able to handle high flood. To tackle all the aforementioned problems caused by erosion and sedimentation, identifying erosion prone areas and proper application of management options on those areas is crucial in hydropower.

The sustainability of water storage of hydropower reservoirs require a balance to be maintained between the volume of sediment deposited and the volume of sediment removed from the reservoir. (Morris and Fan, 1998). The *Gidabo Dam* reservoir is one of the largest reservoirs planned on the Rift valley River Basin involving large investment cost. Therefore; it is important to predict sediment inflow at *Gidabo Dam* and evaluate its consequences on the reservoir and sustain the reservoir through long term optimum sediment management program.

1.2 Statement of the Problem

The major problem in irrigation reservoir sedimentation is one of the most important factors in the planning of a storage-dam, because uncontrolled soil erosion, Poor land use practices and improper mitigation management systems, land degradation resulting in heavy sediment transport in streams and rivers causes significant reduction of the capacity of reservoirs.

Therefore, understanding the impacts of soil erosion and looking for solutions to minimize is essential, it is important to assess the magnitude of the problem so that effective measures can be implemented (Shrestha, 1997).

This study focuses on estimating the sediment yield from *Gidabo Dam* watershed, identifying erosion prone areas in the watershed and proposing alternative management plan to minimize erosion rate in the hydropower reservoir.

1.3 Objective of the Study

1.3.1 General Objective

The overall goal of this study is to model the hydrological processes to estimate the sediment Yield of *Gidabo Dam* hydropower reservoir and identification of most appropriate sediment management strategy of this watershed by making use of the SWAT (Soil and Water Assessment Tool) model.

1.3.2 Specific Objective

- ✓ To estimate the amount of sediment yield of the *Gidabo Dam* by SWAT
- ✓ To estimate the annual specific sediment of *Gidabo Dam* To recommend appropriate mitigation measure to reduce sediment yield of watershed

2. Description of the Study Area

2.1 Location of the Study area

The project area is located in the Abaya-Chamo sub-basin of the Rift Valley Lakes Basin situated in the southern part of Ethiopia, within the administrative Regions of Oromiya and SNNPR. To be more specific, it falls in Abaya district of Borena zone of Oromiya region and Dale district of Sidama zone of SNNPRS (near Dilla town to east of Lake Abaya). The project area lies in the low lands, very close to the Dure and Gola marsh. It lies approximately between 6°20' and 6° 25' N Latitude and 38° 05' and 38°10'E Longitude, a short distance to the east of Lake Abaya and just south of *Gidabo* river flood plain, and at an average elevation of 1190 m a.m.s.l. The upper part of the catchment is covered with thick bushes and shrubs. However middle catchment is occupied with small and scattered bushes and grasses. The lower part mainly comprises of delta and swamp area and is covered with tall grasses. The proposed project area is situated in this part. Some parts of this area serve as dry season grazing for pastoralist.

The irrigation command area as found from the earlier studies may be located about 32 Km from Dilla town.

Gidabo Irrigation Project has been proposed to be commanded by the *Gidabo* River, which is one of the major rivers that drain into Lake Abaya. The *Gidabo* River basin covers a catchment area of about 3440 km² up to its confluence with the Lake Abaya.

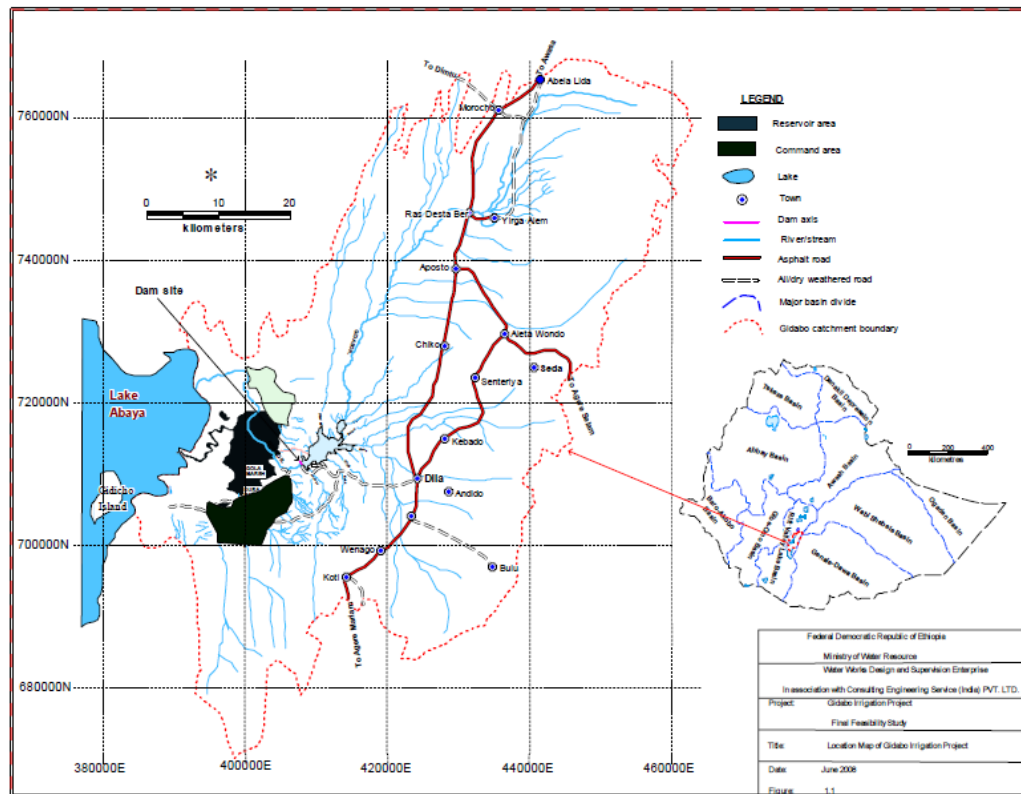


Figure 2.1 Location of the Gidabo Dam site

3. Materials and Methods

3.1 Methodology

The methodology and analysis to be used in this study is mainly with the aid of SWAT model by using the data and materials as explained below. The general methodology of this study is depending on the data which are collected from different organization and also field observation. In this methodology the first part is the prediction of sediment yield in the watershed by using SWAT model for determination of sediment yield at the Reservoir site and to characterize the sub basins in terms of sediment yield.

The conceptual framework of the steps followed during the course of this project is shown below.

- ❖ Set objective
- ❖ Data collection and preparation
- ❖ Import prepared data in to the model
- ❖ Model set up and run
 - Delineate the watershed
 - Create HRUs
 - Model Setup
 - Run the Model
 - ❖ Sensitivity analysis
 - ❖ Calibration and validation

The SWAT (Soil and Water Assessment Tool, Arnold et al., 1998) model is a river basin model developed by US Department of Agricultural Research Service (ARS) in Temple, Texas. SWAT incorporates features of several ARS models and is a direct outgrowth of the SWRRB model (Simulator for Water Resources in Rural Basins) (Williams et al., 1985).

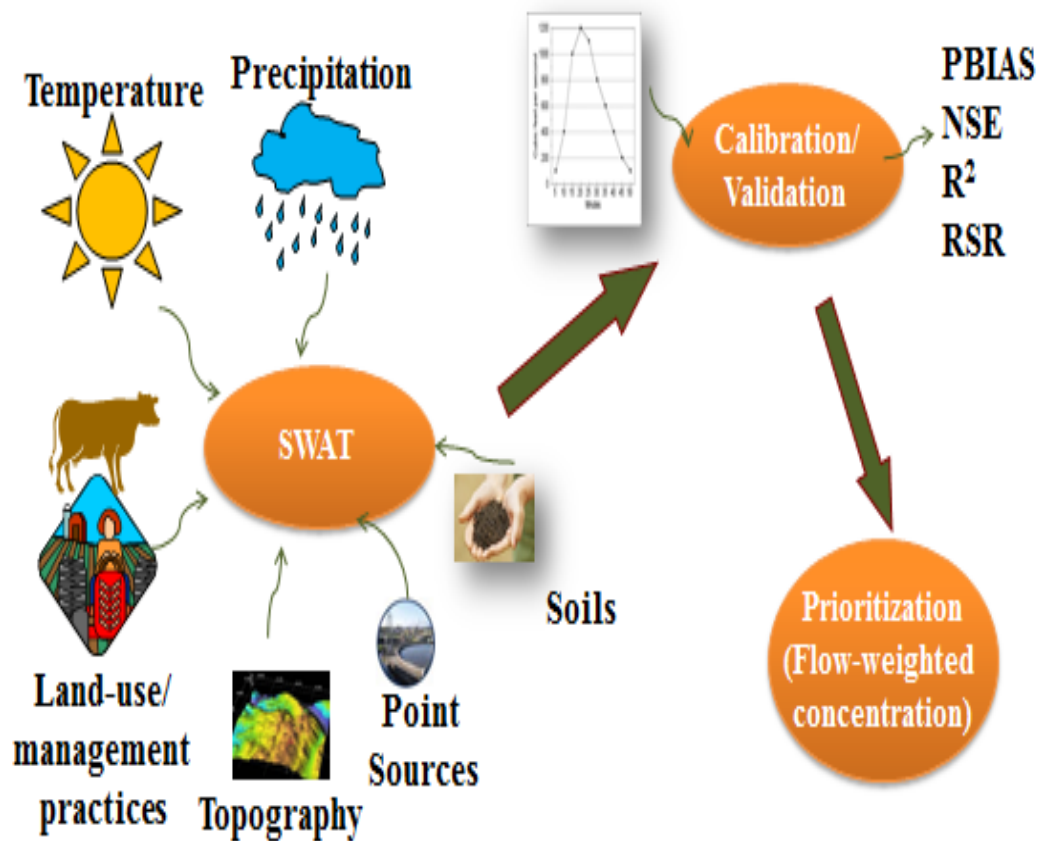


Figure 3.1 Summary of SWAT data entry.

3.2 Sediment modelling

For a watershed in which erosion and sedimentation process is significant, it is important to identify the source erosion and what causes it. In addition to this, it is also very crucial to identify which erosion type is significant in the watershed of interest so that the correct and suitable erosion model can be applied.

SWAT uses a Modified Universal Soil Loss Equation (MUSLE) developed by Williams (1975) to simulate sediment yield from the upland watersheds. MUSLE is a modified version of Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965, 1978) (Neitsch et al., 2011).

$$Sed = 1.292EI_{USLE}K_{USLE}C_{USLE}P_{USLE}LS_{USLE}CFRG$$

Where, Sed is the sediment yield on a given day (metric tons/ha), EI_{USLE} is the rainfall erosion index (0.017 m-metric ton cm/(m² hr)), K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m² hr/(m³-metric ton cm)), C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and $CFRG$ is the coarse fragment factor. The value of EI_{USLE} for a given rainstorm is the product, total storm energy (E_{storm}) times the maximum 30 minutes intensity (I_{30}). The storm energy indicates the volume of rainfall and runoff, while the 30 minutes intensity indicates the prolonged peak rates of detachment and runoff (Neitsch et al., 2011).

$$d = 11.8 (Q_{surf} q_{peak} Area_{hru})^{0.56} K_{USLE} C_{USLE} P_{USLE} LS_{USLE} CFRG$$

Where, Q_{surf} is the surface runoff volume (mm), q_{peak} is the peak runoff rate (m³ / s), $Area_{hru}$ is the area of the HRU (ha), and the other variables in the equation carries the same meaning as described in USLE equation. The equation for surface runoff and peak rate was discussed under hydrologic modelling topic earlier.

Sediment yield estimation is improved because runoff is a function of antecedent moisture condition as well as rainfall energy (Neitsch et al., 2011). Delivery ratios (the sediment yield at any point along the channel divided by the source erosion above that point) are required by the USLE because the rainfall factor used by USLE represents energy used in detachment only.

Delivery ratios are not needed with MUSLE because the runoff factor represents energy used in detaching and transporting sediment (Neitsch et al., 2011). The detail of equations used to calculate K_{USLE} , C_{USLE} , P_{USLE} , LS_{USLE} , and $CFRG$ can be found in Neitsch et al (2011).

3.3 Evaluation of Model Performance/ Efficiency criteria

From the numerical indicator Coefficient of determination (R²), Coefficient of efficiency or Nash Sutcliffe efficiency (NSE) and Percent bias (PBIAS) were selected performance measures for this study.

1. Coefficient of determination (R²)

The coefficient of determination (R²) measures the fraction of the variation in the measured data that is replicated in the simulated model results

$$R^2 = \frac{\left[\sum_i (Q_{m,i} - \bar{Q}_m)(Q_{s,i} - \bar{Q}_s) \right]^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2 \sum_i (Q_{s,i} - \bar{Q}_s)^2}$$

Where, Q_m is observed stream flow on day i (m³/s)

Q_s is simulated stream flow on day i (m³/s) and bars indicates averages.

2. Nash-Sutcliffe efficiency coefficient (NS)

The Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe, 1970) is used to assess the predictive power of the hydrological models. The value of NS varies from 1.0 (perfect fit) to -ve infinity.

$$NS = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2}$$

$$NS = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2}$$

3. Percent bias (PBIAS)

The optimal value of PBIAS is zero, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999) and calculated by equation below.

$$PBIAS = \frac{\sum_{i=0}^n (S_{ob} - S_{sim})}{\sum_{i=0}^n (S_{ob})} * 100$$

Where: S_{ob} is the Observed sediment data; S_{sim} is the simulated sediment data with the respected time.

4. Results and Discussions

4.1 Parameters sensitive to flow

Therefore, it is wise to test the sensitivity of the parameters for flow and sediment separately. Sensitivity analysis was carried out before calibrating the model to save time during calibration.

The 16 parameters listed in Table 4.1 were used in sensitivity analysis for flow calibration by SWAT CUP. The parameter identification was done by using the daily flow data from 1989 to 2014. According to the result from the global sensitivity analysis, the curve number (CN2) was found to be the most sensitive parameter.

Table 4. 1 parameters sensitive to flow depending on P-value and t-stat

S/NO.	Parameter Name	Description of parameters	t-Stat	P-Value	Range of Value	Rank
1	V__CN2.mgt	SCS runoff curve number	-14.94	9.91E-25	35-98	1
2	V__GW_REVAP.gw	Groundwater revap coefficient	8.1806	3.88E-12	0-0.2	2
3	V__HRU_SLP.hru	Average slope steepness	-6.799	1.80E-09	0-1	3
4	V__GW_DELAY.gw	Groundwater delay	5.9423	7.20E-08	0-500	4
5	V__ALPHA_BF.gw	Baseflow alpha factor	-4.26	5.60E-05	0-1	5
6	V__EPCO.bsn	Plant uptake compensation facto	2.4367	0.01707	0-1	6
7	V__BIOMIX.mgt	Biological mixing efficiency	-1.462	0.1478014	0-1	7
8	V__OV_N.hru	Manning's "n" value for Overlan	0.7829	0.4360353	0.01-30	8
9	V__CH_K2.rte	Effective hydraulic conductivity i	0.6651	0.5079169	0.01-500	9
10	R__SOL_K(.).sol	Saturated hydraulic conductivity	-0.619	0.5376019	0-2000	10
11	V__SURLAG.bsn	Surface runoff lag time	0.5542	0.5809776	1_24	11
12	V__RCHRG_DP.gw	Deep aquifer percolation fractio	0.5017	0.6172774	0-1	12
13	V__GWQMN.gw	Threshold depth of water in the	-0.448	0.6551331	0-5000	13
14	V__ESCO.hru	Soil evaporation compensation f	0.3444	0.7314608	0-1	14

4.2 Parameters sensitive to sediment

The most sensitive parameters for erosion simulations were: USLE support practice factor (USLE_P), average slope steepness (HRU_SLP), USLE soil erodibility factor (USLE_K), USLE cover and management factor (USLE_C) channel.

Table 4. 2 parameters sensitive to sediment depending on P-value and t-stat

S/NO.	Parameter Name	Description of parameters	t-Stat	P-Value	Range of Valu	Rank
1	V__USLE_P.mgt	USLE support practice factor	36.8493744	7.25E-55	0-1	1
2	V__HRU_SLP.hru	Average slope steepness	20.6671742	2.56E-35	0-1	2
3	R__USLE_K(.).sol	USLE soil erodibility factor [t.ha.h.	6.50404116	4.77E-09	0-0.65	3
4	R__USLE_C(.).plant.dat	USLE cover and management facto	-3.1047103	0.00257048	0.001-0.5	4
5	V__BIOMIX.mgt	Biological mixing efficiency	1.33141151	0.18653181	0-1	5

4.3.1 Model calibration to flow

The model was calibrated by using the values of parameters that were identified as highly sensitive to runoff as it was described under sensitivity analysis section by SWAT CUP software. The value of coefficient of determination (R) and the Nash-Sutcliffe efficiency (NS) for Monthly runoff in 1989 to 2006 were 0.78 and 0.77 respectively.

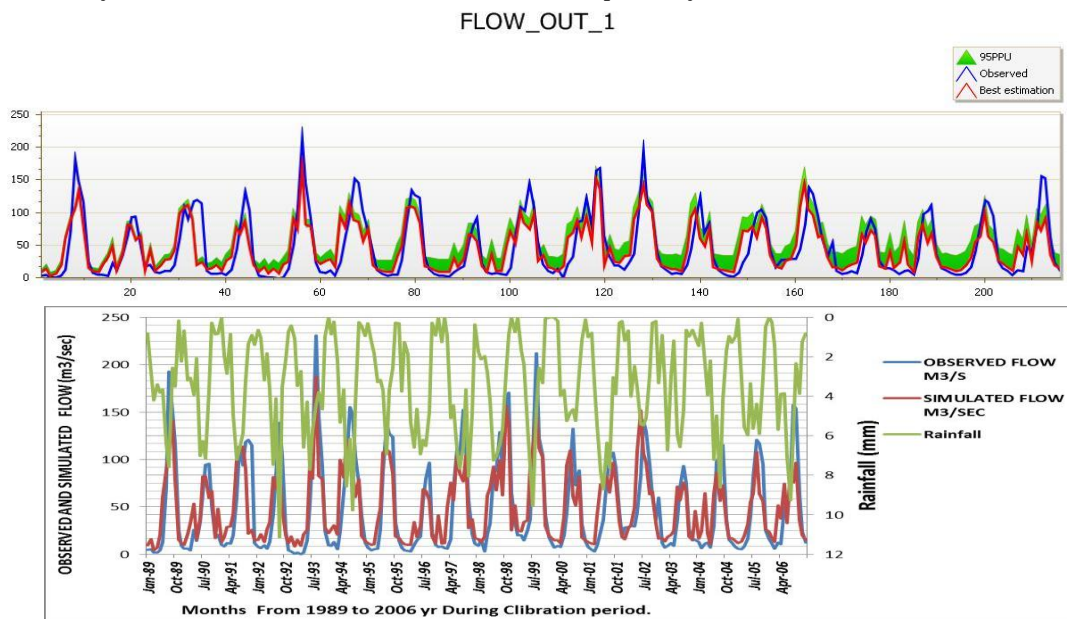


Figure 4. 1 observed and simulated monthly runoff for calibration period 1989-2006.

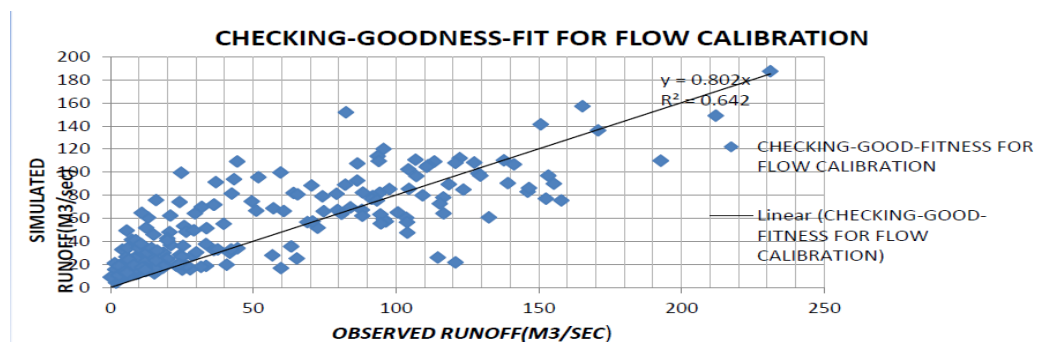


Figure 4. 2 Goodness-of-fit for observed and simulated daily runoff

4.3.2 Model Validation to flow

Validation is a process of proving the performance of model. The model validation was carried out for Monthly runoff. The value of coefficient of determination (R) and the Nash-Sutcliffe efficiency (NS) for Monthly runoff 2007 to 2015 were 0.54 and 0.53 respectively.

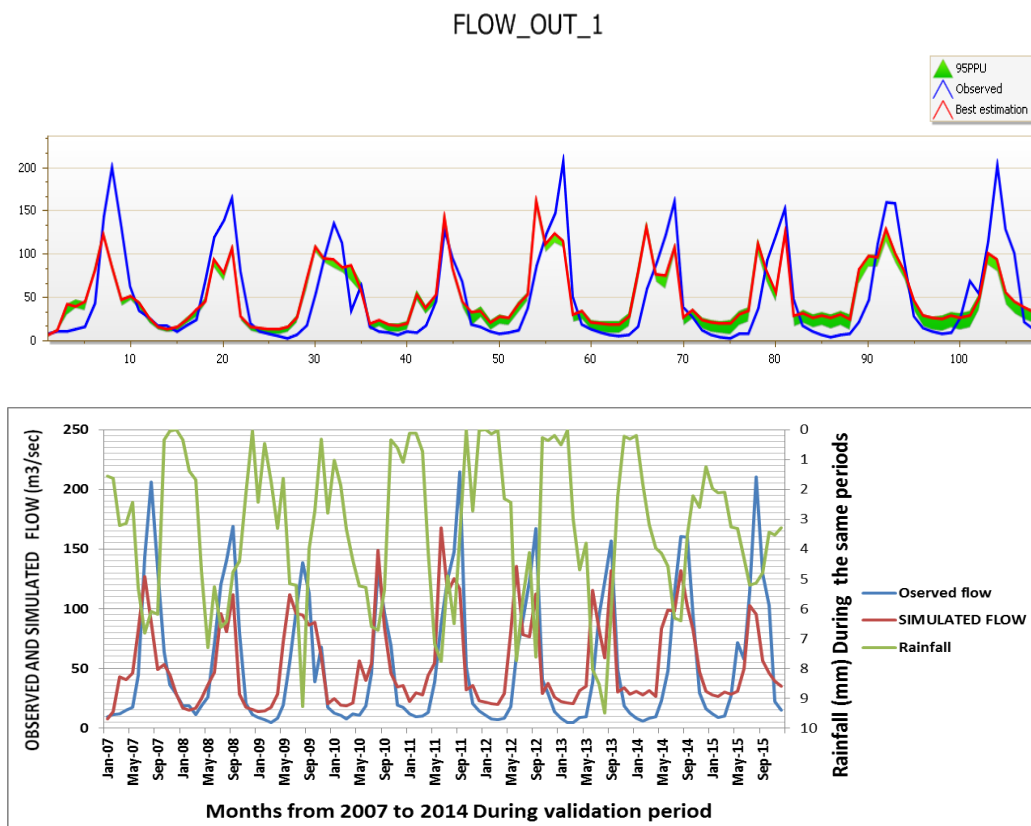


Figure 4. 1 observed and simulated monthly runoff for validation period 2007-2015.

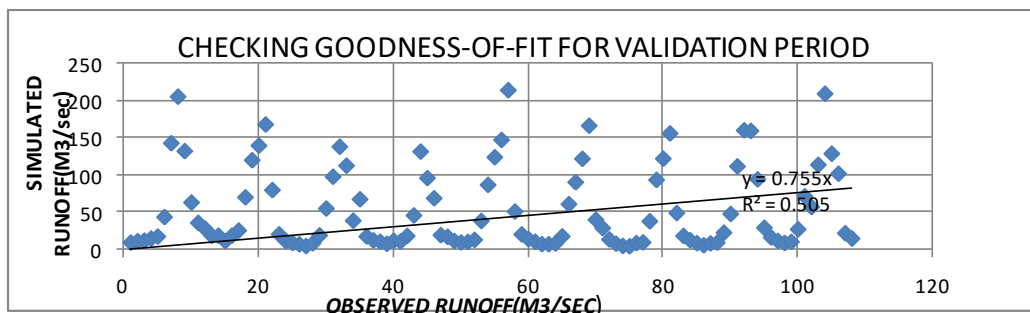


Figure 4. 2 Goodness-of-fit for observed and simulated for validation period 2007-2014.

4.4.1 Model calibration for sediment

SWAT model was first calibrated and validated to flows, then to sediment. The model was calibrated for sediment by comparing annual model simulated sediment load against annual measured sediment load. The model was calibrated for observed sediment data for the calibration period (1990-2010) of monthly time step with value of

coefficient of determination (R^2)(0.69) and the Nash-Sutcliffe efficiency (NSE) (0.68).

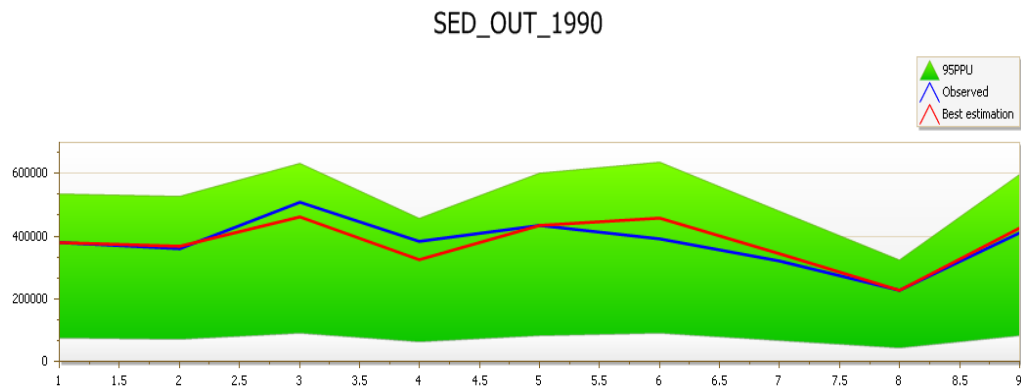


Figure 4.3 observed and simulated sediment load for calibration period 1990 to 2010 year.

4.4.2 Model validation for sediment

The model was validated for observed sediment data for the validation period (2011-2014) of monthly time step with value of coefficient of determination (R^2) (0.66) and the Nash-Sutcliffe efficiency (NSE) (0.58) and PBIAS value of (1.88).

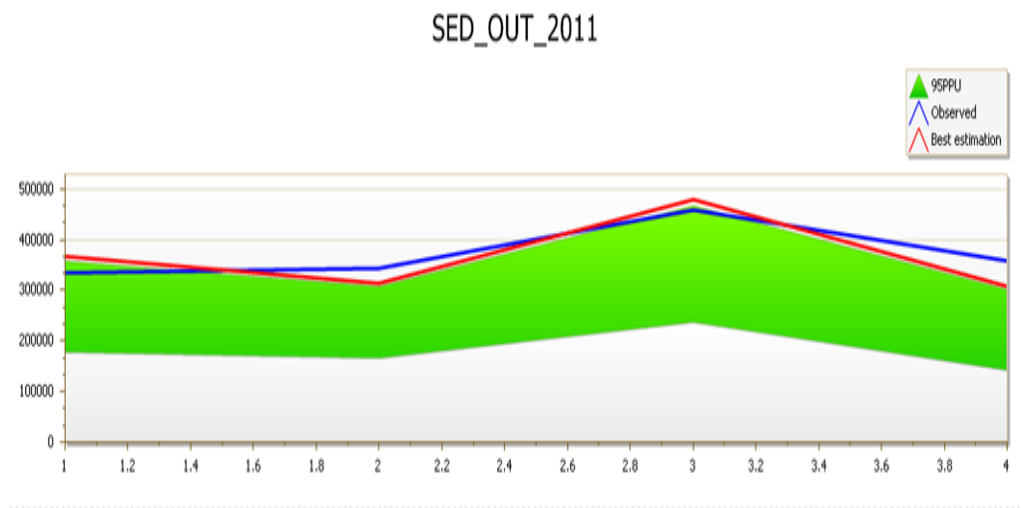


Figure 4.6 Observed and simulated sediment load for validation period 2011 to 2014 year.

4.5. Sediment load

The total observed and simulated sediment yield (load) from *Gidabo Dam* sub-catchment during the period from 1990 to 2010 was 3,442,064 tons and 3,446,300 tons respectively.

The specific sediment yield based on the observed and simulated sediment load by SWAT model from *Gidabo Dam* watershed of area 2532 km² was 955.598 tons/km² and 956.774 tons/km² respectively. Based on this result, the SWAT model gives quite good estimation of the sediment yield from the catchment. In the same manner, the total annual simulated sediment load from watershed for 9 calibrating years was estimated using the SWAT model was 3,442,064 tons/9yr=382,451.556 tons. The annual specific sediment yield from the watershed can be calculated as the ratio of the total annual sediment yield to the area of the watershed and the value is 106.178 tons/km²/yr.

4.5.1 Sediment concentration

In addition to sediment load or sediment yield from a basin, SWAT also simulates the concentration of sediment in mg/kg or ppm(parts per million) from a basin. The concentration of suspended sediment in the stream is related to the amount of discharge flowing in the river. But, this may not be the case in the area where gully erosion, land sliding and mass wasting are dominant factors that add sediment to the river.

Particularly for Gilgel Gibe-I sub-watershed is shown in Figure shows that the sediment concentration in the stream is high where the discharge is high. There is high sediment concentration (8919ppm) on 22-Jan-2013 for a discharge of 335.25 m³/s.

Table 4. 4 Sediment concentrations by weight and discharge of Gilgel Gibe-I

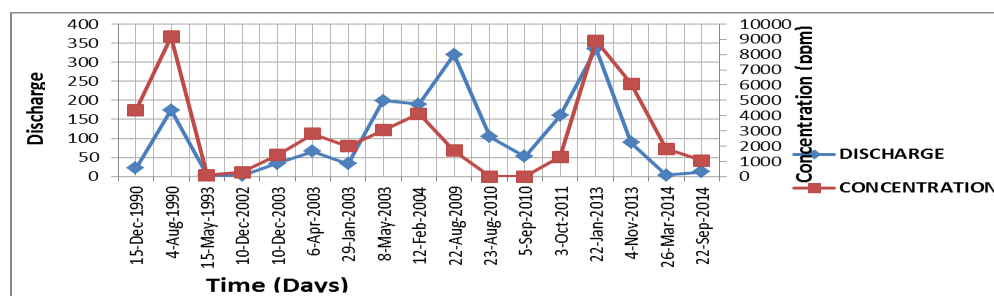


Figure 4.7 concentrations by weight and discharge 1990-2014 simulated and observed.

5. Conclusions and Recommendations

5.1. Conclusions

The watershed parameters were derived from DEM resulting in 15-sub-basins, Sub-basins were further broken down in to hydrological response units based on the land use and soil data. This resulted in 72 HRU's.

Sensitivity analysis is performed to select important model parameters; Automatic calibration SWAT CUP is performed for stream flow using measured data at Asendabo gauging station for a period of 1989-2006. It is shown that the model could adequately represent stream flow

for monthly time steps. It is shown that the model performed well with ENS and R2 0.68 and 0.67 respectively for flow calibration.

The model was validated for the stream flow for the period of 2007-2014. The model performed well monthly time steps with ENS and R2 0.58 and 0.57 respectively.

The model is then calibrated with sediment flow data that is taken from ministry of water resource and energy during (1990-2010).

The global sensitivity analysis of the SWAT parameters showed that runoff is most sensitive to curve number (CN), followed by Ground water revap coefficient (GW_REVAP), effective Average slope steepness (HRU_SLP). The sensitivity analysis of the SWAT parameters showed that sediment yield is most sensitive to upland factors such as USLE soil erodibility factor (USLE_K), USLE cover and management factor (USLE_C) and USLE support and practice factor (USLE_P).

The specific sediment yield based on the observed and simulated sediment load by SWAT model from the watershed of area 3602 km² was 955.598 tons/km² and 956.774 tons/km² respectively.

The annual specific sediment yield from the watershed can be calculated as the ratio of the total annual sediment yield to the area of the watershed and the value is 106.178 tons/km²/yr. Applying filter strip and terracing (stone bunds) in low slope areas of the catchment could give potential effect of best management practice.

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