ASSESSMENT OF THE USE OF REMOTELY SENSED RAINFALL PRODUCTS FOR RUNOFF SIMULATION IN THE UPPER BLUE NILE BASIN OF ETHIOPIA

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ABSTRACT

The successful application of hydrological models depends not only on the model structure and spatial and temporal scale, but also on the accuracy of the rainfall as a main input. In many developing countries like Ethiopia, the rainfall observation network is relatively sparse. In recent years, several techniques have been developed for estimating rainfall using satellite data. The Climate Prediction Center Morphing Method (CMORPH) is one of them and it uses motion vectors derived from half-hourly interval geostationary satellite infrared imagery to propagate the relatively high quality precipitation estimates derived from passive microwave data.

The main objective of this research is to compare the performance of SWAT model using rainfall input data from remotely sensed and ground measured data for Gilgel abbay catchment. Based on the results obtained, it can be said that SWAT model yields good results for the satellite rainfall input data when compared to in situ rainfall input data. Thus, CMORPH rainfall products can possibly be used for the un-gauged catchment in the Upper Blue Nile Basin. It is recommended to test the CMORPH rainfall product over other catchments with relatively dense in situ data in the Upper Blue Nile Basin with the same CMORPH and finer spatial resolutions products.

***Keywords**: Ethiopia, Gilgel abbay; Koga; SWAT; Satellite rainfall data; in situ rainfall data;*

INTRODUCTION

Hydrological models are used to estimate runoff and to predict extremes events like floods and droughts. Particularly, hydrological models are useful to simulate rainfall runoff process for better understanding of hydrology and runoff generation mechanisms of a catchment. The successful application of such models depends not only on the model structure and the different time and space associated, but also on the accuracy of rainfall as a main input. The accurate and timely quantitative precipitation estimates are essential for forecasting and mitigating flood hazards [1], landslide potential [2], assessing water resources, forecasting model verification [3], and more generally, it improves the understanding on the hydrologic cycle. Nowadays, remote sensing imagery acquired and processed in real time can provide near-real-time rainfall at relevant spatio-temporal scales (tens of kilometers and sub-daily) [2], [4], [5], [6]. Remote sensing has increasingly become a viable data source to supplement the conventional hydrological rainfall-runoff simulation, particularly for inaccessible regions or complex terrains and in areas where there are no rainfall and stream flow gauging stations [5], [6].

Artan [7] showed the improved performance of remotely sensed precipitation data when a hydrological model was calibrated with satellite data rather than gauge rainfall over four sub-basins of the Nile and Mekong River. In recent years, several techniques have been developed for estimating rainfall using satellite imagery. The Climate Prediction Center Morphing Method (CMORPH) is one technique which uses motion vectors derived from half-hourly interval geostationary satellite infrared imagery to propagate relatively high quality precipitation estimates derived from passive microwave data. Moreover, the shape and intensity of the precipitation features are modified (morphed) during the time between microwave sensor scans by performing a time-weighted linear interpolation. This process yields spatially and temporally complete microwave-derived precipitation analyses, independent of the infrared temperature field. CMORPH showed substantial improvements over both simple averaging of the microwave estimates and over techniques that blend microwave and infrared information but that derive estimates of precipitation from infrared data when passive microwave information is unavailable [8]. In this research work, the CMORPH product with a spatial resolution (0.25^0 by 0.25^0) and three hourly rainfall data from January 2003 to December 2008 were used for calibration and validation of the hydrological model. The results are compared with the results obtained from in situ rainfall data for the same simulation periods.

The objective of this study is to evaluate the suitability of satellite rainfall product for stream flow simulation in a mountainous watershed like Upper Blue Nile Basin. Soil and Water Assessment Tool (SWAT) model is used to simulate the stream flow for both in situ dataset and CMORPH rainfall product.

DESCRIPTION OF THE STUDY AREA

The Gilgel abbay catchment is located in the Northwest part of Ethiopia between $10^0$56' to $11^0$51' N latitude and $36^0$44' to $37^0$23' E longitude. The catchment contributes the largest inflow into Lake Tana and covers an area of 3,802 km^2. The elevation of Gilgel abbay catchment varies from 1787m to 3518m a.m.s.l. The location map and the digital Elevation Map (DEM) of the study area is shown in Fig. 1. The catchment falls within the cool semi-humid agro-climatic zone with mean annual temperature of 11.5°C to 17°C.

Rainfall in the Gilgel abbay catchment originates from moist air coming from Atlantic and Indian oceans following the north-south movement of the ITCZ. There is a high spatial and temporal variation of rainfall in the study area. The main rainfall season which accounts around 70-90% of the annual rainfall occurs from June to September. Small rains also occur sporadically during February/March to May [9]. The catchment has two gauged sub-catchments, Gilgel abbay and Koga catchments having a size of 1656 km^2 and 299 km^2 respectively.

DATA USED

Seven meteorological stations data, three of them located within and four outside the catchment, were collected from National Meteorological Service Agency. The data includes rainfall, maximum and minimum temperature, relative humidity, wind speed and sunshine hour. Six years daily and monthly meteorological data from 2003 to 2008 were available for the study. The meteorological stations in the catchment area used for the analysis are shown in Fig. 2.

Before the rainfall data were used as input for the model, the data were first checked for consistency and homogeneity. Following a rough screening of and plotting the data, relative consistency and homogeneity test is done with double mass analysis, and the result showed that the data were consistent and homogeneous.

The satellite rainfall data of the catchments were taken from CMORPH product. The catchment was represented by nine grid boxes. Each grid box has an area bounded by the geographic coordinate of 0.25^0 lat and 0.25^0 long. Three hourly rainfall data was extracted from January 2003 to December 2008 for each grid box.

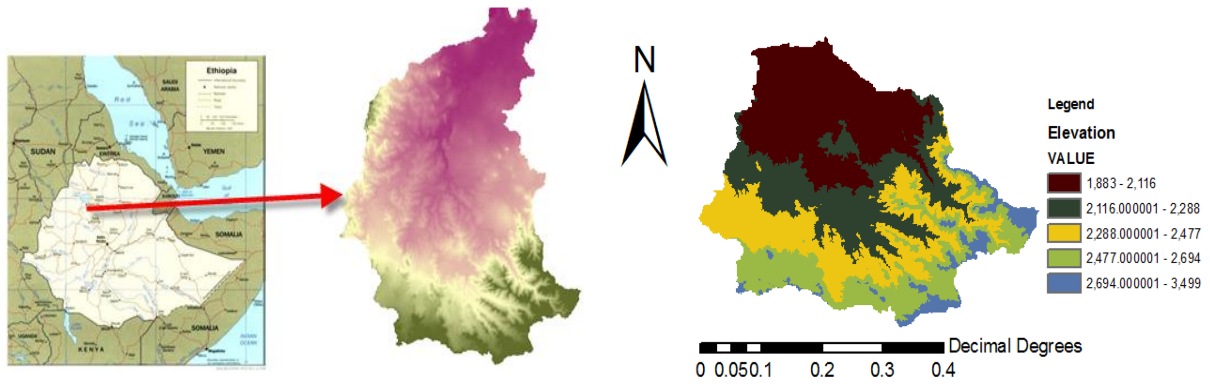


Figure 1 Location map and DEM of gauged Gilgelabbay catchment.

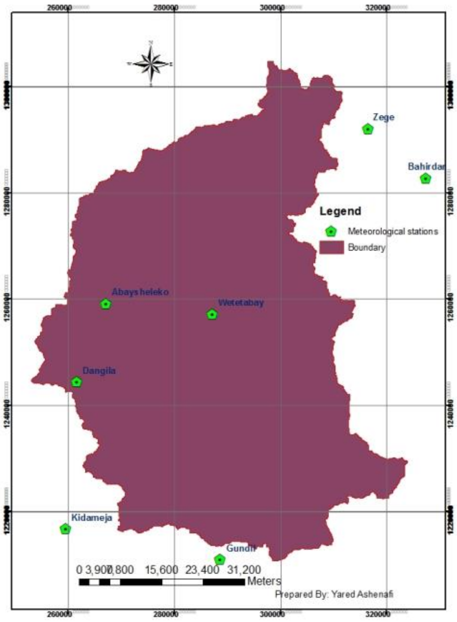


Figure 2 Meteorological stations in the catchment area

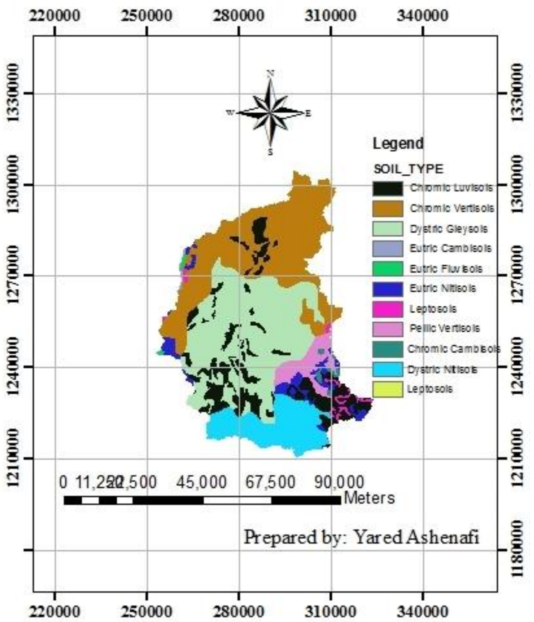
The stream flow data which was used to calibrate the model were collected from Ministry of Water Resources, Hydrology Department. There are two river gauging stations in the catchment: Gilgel abbay and Koga sub-catchments. These two stations are located just upstream of the confluence of Gilgel abbay and Koga rivers. Six years daily flow data at the two gauging stations were used for the study.

Soil data including distribution of soil types and the various parameters describing the soil hydrological and textural properties are required as input to the SWAT model. The soil parameters were obtained from Abbay River Master Plan Project prepared by BCEOM [10]. The shape files which describe the distribution of soil in the study area with 1:250,000 scale were also obtained from Ministry of Water Resources.

The spatial land use distribution and the list of specific land use parameters required by the model were taken from a land use/land cover map prepared by WBISPP in 2000 [11]. The Soil and the land use map of the catchment are shown in Fig. 3.

METHODOLOGY

The Soil and Water Assessment Tool (SWAT) model is a continuous-time, semi-distributed, process based river basin model [12]. It was developed to evaluate the effects of alternative management decisions on water resources and nonpoint-source pollution in large river basins. The model was originally developed for the United States Department of Agriculture –Agricultural Research Service (USDA-ARS) to predict the impact of land management practices on water,



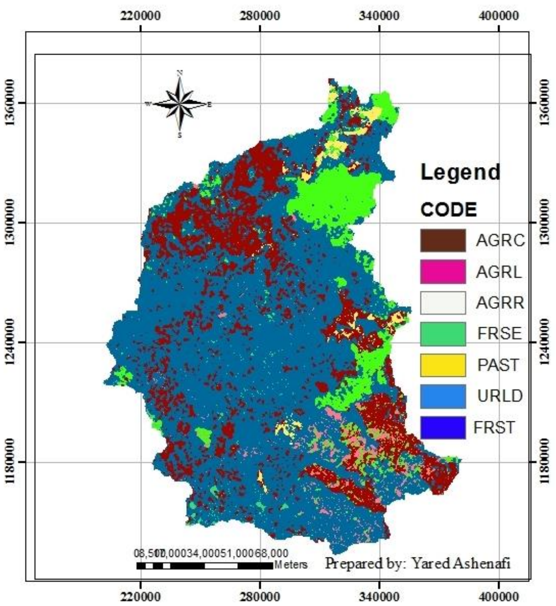


Figure 3 Soil and Land use map of the Gilgel Abbay

sediment, and agricultural chemical yields in large un- gauged basins.

Currently the model is being applied worldwide with reported success. Gassman [13] provided further description of SWAT, including SWAT version 2005, and also presented an in-depth overview of over 250 SWAT-related applications that were performed worldwide including countries like Tanzania, Kenya, Ethiopia, Rwanda, Uganda and Burundi.

SWAT provides two methods for estimating surface runoff: the Soil Conservation Service (SCS) curve number method and the Green and Ampt infiltration method. Even though the latter method is better in estimating runoff volume accurately, its sub daily time step data requirement makes it difficult to be used for this research. Hence, the SCS curve number method was used.

The SCS method [14] computes direct runoff through an empirical equation that requires rainfall and a watershed coefficient as input. The watershed coefficient is called the Curve Number (CN), which represents the runoff potential of the land cover soil complex. This model involves relationship between land cover, hydrologic soil class and CN.

The method is based on the following equation:

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R - I_a + S\right)} \qquad (1)$$

Where:

- Q_{surf} : Accumulated runoff or rainfall excess (mm),
- R_{day} : Rainfall depth for the day (mm),
- I_a : Initial abstraction which includes surface storage, interception and infiltration prior to runoff (mm),
- S: A retention parameter (mm).

The retention parameter varies spatially due to changes in soil types, land use, management and slope and temporally due to changes in soil water content. It is mathematically expressed as:

$$S = 25.4 * \left(\frac{1000}{CN} - 10\right) \qquad (2)$$

For identification of soil hydrologic groups, the model uses the Natural Resource Conservation Service (NRCS) classification, which identifies four hydrologic groups (A, B, C, & D) based on infiltration characteristics of the soils. Group A, B, C and D soils have high, moderate, slow, and very low infiltration rates with low, moderate, high, and very high runoff potential, respectively. The initial abstraction, *Ia*, is commonly approximated as 0.2S and substituting this value in Eq. (1) it becomes:

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)} \qquad (3)$$

Though Eq. (3) is used for runoff generation, SWAT has other mathematical equations governing the biophysical relationships and runoff generation mechanisms. The spatial distribution of different soil types and land use are important factors that affect the overall hydrology of a watershed. SWAT model needs the soil and the land use data in shape file format for defining lumped land areas called Hydrological Response Units (HRU). SWAT's soil database requires basic physical and chemical properties of each soil type in the watershed. The gauged Gilegel abay catchment was divided into smaller 28 HRU's as shown in Fig. 4. The gauging station at Merawi (the outlet) was used to calibrate and validate the model output.

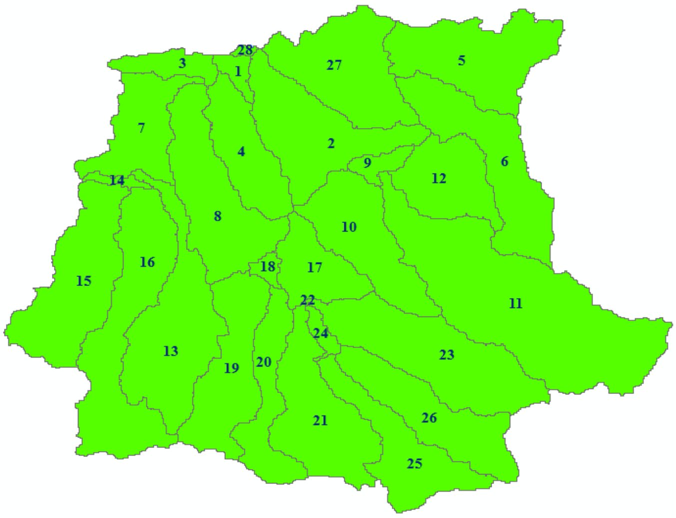


Figure 4 The HRUs of the Gilgel abay catchment

MODEL CALIBRATION AND VERIFICATION

The initial values of the model parameters were calibrated against observed discharge whereby the model parameters are adjusted until the observed data and the model output shows acceptable level of agreement. This level of goodness of fit is evaluated by objective function that measures the level of agreement between the observed data and the model output [15]. Usually two objective functions are considered: goodness of water balance and overall goodness agreement of shape of the hydrograph measured by relative volume error and Nash-Sutcliffe coefficient respectively.

EVALUATION OF MODEL PERFORMANCE

Model simulation results were evaluated by using mean, standard deviation, regression coefficient (R^2), and the Nash and Suttcliffe (ENS) simulation efficiency [16].

The regression coefficient (R^2) is the square of the Pearson product–moment correlation coefficient and describes the proportion of the total variance in the observed data that can be explained by the model. The closer the value of R^2 to 1, the higher is the agreement between the simulated and the measured flows. It is calculated using Eq. (4).

$$R^2 = \left[\frac{\sum_{i=1}^{N} \left(Q_{obs} - \overline{Q}_{obs}\right)\left(Q_{sim} - \overline{Q}_{sim}\right)}{\left[\sum_{i=1}^{N} \left(Q_{obs} - \overline{Q}_{obs}\right)^2\right]^{0.5} \left[\sum_{i=1}^{N} \left(Q_{sim} - \overline{Q}_{sim}\right)^2\right]^{0.5}} \right]^2 \quad (4)$$

Where: -

N: Number of compared values

Q_{obs} : Observed flow

$\overline{Q}_{obs}$: Observed mean

Q_{sim} : Simulated flow

$\overline{Q}_{sim}$: Simulated mean

ENS simulation efficiency indicates the degree of fitness of the observed and simulated hydrographs [17]. ENS can have values ranging from -∞ to 1. If the simulation is accurate, then ENS equals to one. It is calculated using Eq. (5) with the same variables defined above.

$$E_{NS} = 1 - \frac{\sum_{i=1}^{N} \left(Q_{obs} - Q_{sim}\right)^2}{\sum_{i=1}^{N} \left(Q_{obs} - \overline{Q}_{obs}\right)^2} \quad (5)$$

The deviation of runoff volume (D_v) is also a goodness of fit test that statistically compares measured and simulated volume of discharge during an event, providing information on how well the overall water balance is being modeled. A value of zero indicates no difference between measured and simulated volumes. A positive D_v indicates under estimation of simulated volumes, whereas a negative D_v indicates over estimation of simulated volumes

$$D_v = \frac{\sum_n Q_{obs} - Q_{sim}}{\sum_n Q_{obs}} \quad (6)$$

RESULT AND DISCUSSIONS

Sensitivity Analysis

The sensitivity analysis was carried out for a period of six years, which included both the calibration and validation period (from January 1st 2003 to December 31st 2008). Even though 28 parameters with ten intervals of Latin Hypercube (LH) sampling (totally 280 iterations) were used for the sensitivity analysis of SWAT model, only 10 parameters revealed meaningful effect on daily and monthly flow simulation of the Gilgel abbay Sub-catchment. The Curve Number (CN_2) is the most sensitive of all. Table 1 shows the list of the most sensitive parameters and the categories of sensitivity. As expected, land use composition is the most important governing factor in runoff generation (represented by CN in the model) in the upper Blue Nile. The base flow component of Gilgel Abbay has shown a high contribution of ground water to the stream flow (as represented by parameter Rchrg_dp).

Table 1: Results of the sensitivity analysis for gauged Gilgel abbay sub-catchment

Rank	Parameters	Description	Lower bound	Upper bound	Mean Relative sensitivity (MRS)	Category of sensitivity
1	CN_2	Initial SCS CN II value	-25%	25%	2.02	Very high
2	Rchrg_dp	Deep aquifer percolation fraction	0	1	1.78	Very high
3	GWQMN	Threshold water depth in the shallow aquifer for return flow to occur (mm)	0	5000	1.12	Very high
4	GW_REVAP	Ground water "revap'	0.02	0.2	0.38	High
5	canmx	Maximum canopy storage (mm)	0	10	0.19	Medium
6	slope	Average slope steepness [m/m]	0	0.6	0.13	Medium
7	Sol_z	Soil depth (mm)	0	3000	0.11	Medium
8	Sol_Alb	Soil albido	0	0.25	0.091	Medium
9	Sol_K	Saturated hydraulic conductivity [mm/hr]	-25%	25%	0.091	Medium
10	ESCO	Soil evaporation compensation	0	1	0.057	Medium
11	Alpha_BF	Base flow alpha factor	0	1	0.053	Medium
12	GW_DELAY	Ground water delay	0	500	0.035	Small
13	REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur	0	500	0.031	Small
14	CH_K_2	Effective Hydraulic conductivity in main channel alluvium	0	150	0.0085	Small

Calibration and Validation with satellite rainfall data

The stream flows simulated with satellite rainfall as an input for the period of January 2003 to December 2005 were used for comparison. The comparison between the simulated and observed stream flow showed that the shape of the rising limb and peak flows are relatively well simulated by the model. Comparisons between the observed and simulated hydrographs are shown in Fig. 5, and the model performance result obtained is summarized in the Table 2 on daily and monthly time step. The performance of the calibration on daily basis was poor as compared to the monthly time step. This may be due to the slow response behavior of the ground water components that was not captured well in the model.

Table 2: Summary of model performance with satellite rainfall for Gilgel abbay sub-catchment

Model Name	Satellite rainfall							
	Daily				Monthly			
	Calibration		Validation		Calibration		Validation	
	R^2	ENS	R^2	ENS	R^2	ENS	R^2	ENS
SWAT	44	43	55	38	83	82	89	77
Relative volume error (%)	4.4		4.2		-11		-10	

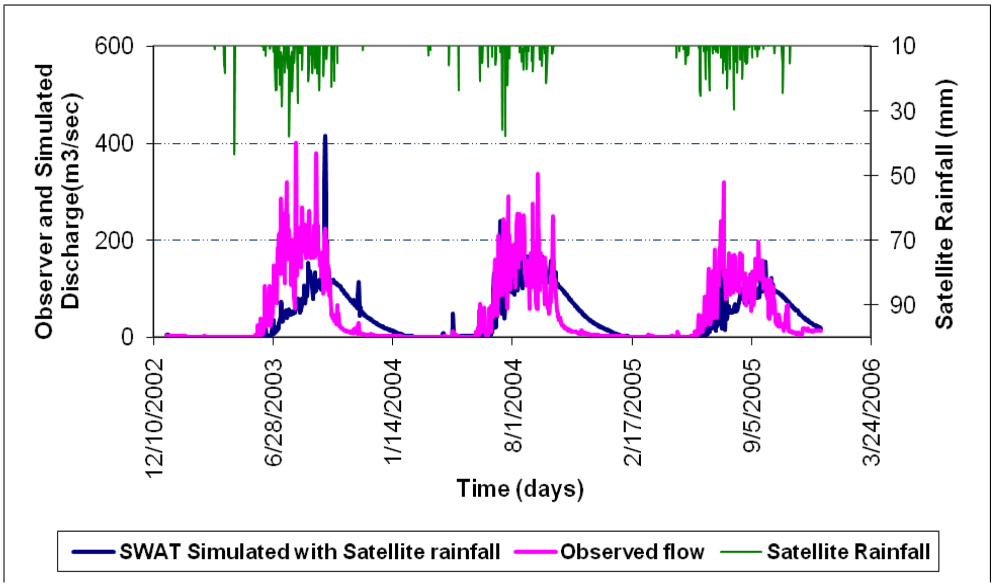


Figure 5. Daily SWAT simulated graph with Satellite rainfall

Comparisons SWAT Model Performance for Satellite and in Situ Rainfall Data (2003-2005)

The performance measures of the two simulations sets are summarized in Table 3. The graphical comparison was done as shown on Figures 6 and 7. All performance statistics indicate that the stream flow simulations were of better agreement when the model was calibrated with satellite data than when the model was calibrated with rain gauge data.

One of the reasons for better performance the satellite could be the inadequacy of point rainfall measurements to represent spatial rainfall. There are only three stations in the catchment and the satellite data gave possibly a good representation of the aerial rainfall.

Comparison of model parameters that control the overland flow was done based on results of rainfall inputs of satellite and gauging stations. One of the highly sensitive parameter that controls the surface runoff was the CN. Increasing the CN values result in increasing runoff. The rain gauge and satellite CN values were higher than the standard SCS values.

Table 3: Summary model performance result with input rainfall from Satellite and gauging stations

Model Name	Description of rainfall data type	Daily				Monthly			
		Calibration		Validation		Calibration		Validation	
		R^2	ENS	R^2	ENS	R^2	ENS	R^2	ENS
SWAT	Satellite Rainfall	44	43	55	38	83	82	89	77
	Rain gauge	43	39	56	-9.40	72	70	57	-9.87

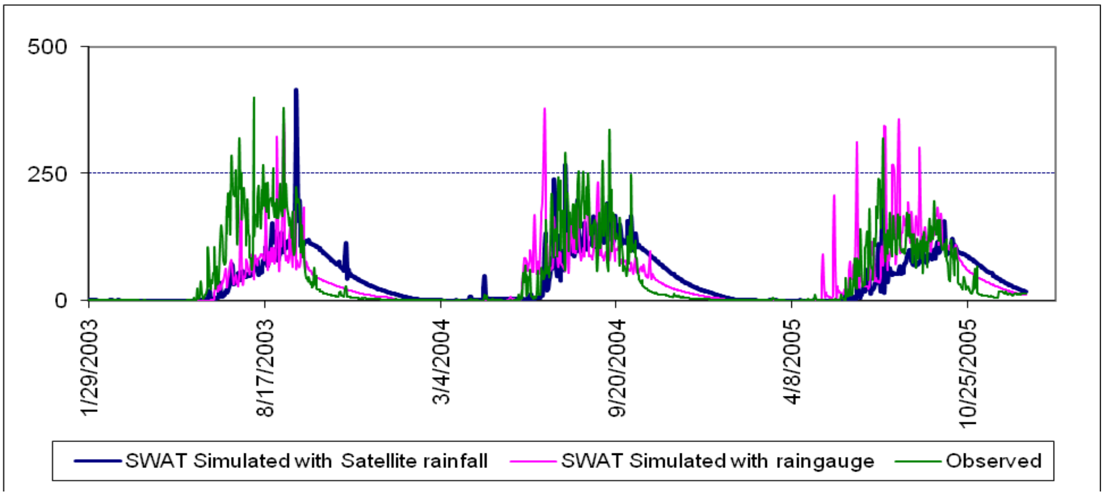


Figure 6 Comparison of daily simulated and observed hydrograph from SWAT model for satellite and rain gauge input rainfall.

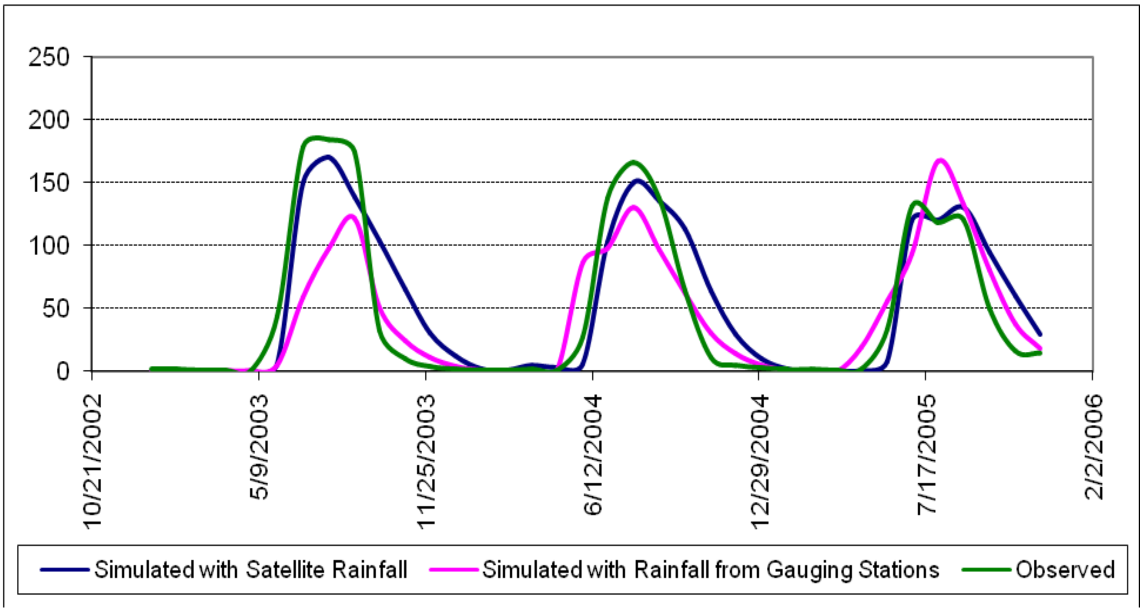


Figure 7 Comparison of monthly Simulated and observed hydrograph from SWAT model for satellite and rain gauge input rainfall.

CONCLUSION

SWAT model was applied to simulate the stream flow hydrographs of catchments observed at Merawi station on daily and monthly time step. After checking and analyzing the consistency of the data, model calibration and validation has been done. Moreover, the performance of the model has been tested by considering rainfall data obtained from satellite as well as in situ datasets. Based on the results obtained, SWAT model performed relatively better for satellite rainfall input data than the data from rain gauges stations. Thus, it can be said that the CMORPH rainfall product has a potential for use in water resource management and hydrologic predictions for un-gauged catchments in the Upper Blue Nile. However, the authors recommend testing the CMORPH rainfall product over other catchments with relatively dense in situ data in the Upper Blue Nile Basin with the same CMORPH and finer spatial resolutions products.

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