Investigating the Water Balance using SWAT model for Lake Tana basin, Ethiopia

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Abstract

Although, the Nile is the longest river in the world (6,695 Km) and the fifth in area with about 3 million Km^2, the total flow of the Nile is 84 billion m^3 at Aswan, which represent about 1.2% of the precipitation on the basin area. The Blue Nile, originating from Lake Tana in the Ethiopian highlands, is the largest contributor with 59% of the Nile flow at Aswan. Lake Tana basin includes more than 40 torrents discharging in Tana Lake, but the major torrents are; Gilgel Abbay, Gumera, Ribb, and Megech. Such four torrents contribute more than 93% of the inflow to the Lake. The catchment area of the basin is approximately 15,000 Km^2 and rises up to 4000 m above sea level - at the northern part. The present paper focuses on studying the water balance in Lake Tana basin via Soil and Water Assessment Tool (SWAT) model. SWAT is a semi-distributed physical model and considered as compatible tool to study such basins with complicated topography and data scarcity. Data obtained from online resources: the DEMs produced by ASTER Global Digital Elevation Model V003, Soil map is obtained from the Food and Agriculture Organization of the united nation (FAO), and Land Use Land Cover (LULC) is obtained from the GIS portal of the International Livestock Research Institute (ILRI). A SWAT model was applied to study the water balance. The SWAT model gave satisfactory results that agree well with the ground runoff observations for the basin. The model was calibrated by two methods; SUFI-2 and GLUE. The Ribb calibration and validation shows good results with NSE > 0.70 and R^2 > 0.75. Both SUFI-2 and GLUE gave acceptable results for discharge calibration with p-factor more than 70% and r-factor 0.97 for GLUE and 1.17 for SUFI-2. The results reveal that about 85% of the annual precipitation is lost by evapotranspiration in Lake Tana basin. The outflow at the lake exit is about 4.47 billion m3/year while it was 3.93 billion m3/year as reported by Shahin (1985) [1]. Although, the balance at the lake outlet shows deficiency in the water balance with about 27%, the outflow from the lake gives satisfactory results.

Keywords: Lake Tana, SWAT modeling, Water Balance, Remote Sensing

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I. Introduction

The Nile River is ranked as the main source of water in Egypt since contributes about 55.5 billion m^3/year according to the 1959's agreement between Egypt and Sudan. However, Egypt faces a water challenge because of the high population growth, increase in agricultural areas, development of industry, and rise in the living standards. As shown in Fig (1-a), three main sources contribute the water volumes in the Nile River; western nile from Bahr El Ghazal, southern nile from Bahr El Jebel, and eastern nile from the Ethiopian Plateau. The Nile basin is 3.1 million Km², which represent approximately ten percent of the African continent. The Ethiopian highlands provide 86% of the Nile flow; 59% from the Blue Nile, 14% from Baro-Akobo Sobat, and 13% from Atbara Swain, (2011) [2]. The Blue Nile River flows from the Ethiopian Plateau with elevations more than 4000 meter above sea level (m a.s.l.) to an elevation of about 350 (m a.sl.) in Khartoum. The basin extends from 70 40`N to 160 2`N latitude and 320 30`E to 390 49`E longitude. The Blue Nile is divided into 18 sub-basins, as shown in Fig. (1-b), namely, Lower Blue Nile, Upper Blue Nile, Dinder, Rahad, Tana, Beshelo, Beles, Dabus, Diddessa, Jemma, Muger, Guder, Fincha, Anger, Wenbera, South

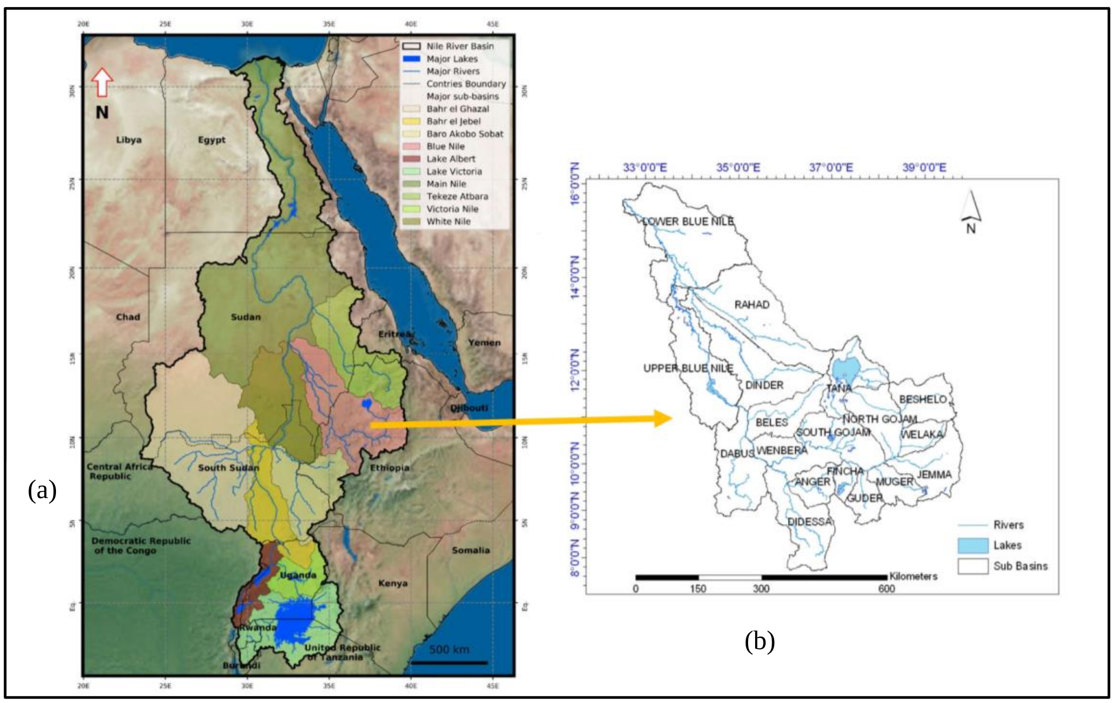

Fig. 1 (a) Location of the Nile River Basin and its major sub-basins [3] **(b) Blue Nile sub-basin** [4]

Gojam, North Gojam and Welaka. The current study is intended to study the water balance in Lake Tana basin, since it is the originating source of the Blue Nile and the largest fresh water lake in Ethiopia.

Varies previous studies were oriented to study the water balance of Lake Tana Basin, some of such studies will be illustrated next. Conway (1997) [5] developed a grid-based physical water balance model to study the upper Blue Nile, particularly Lake Tana and Dabus Swamps, excluding both land cover/use and soil characteristics. The model showed the sensitivity of the water budget to runoff given the seasonal distribution of rainfall. Kebede et al. (2006) [6] studied the water balance in lake Tana and its sensitivity to fluctuation in rainfall based on a mathematical approach to define the change in the surface levels. Analysis of results revealed that the lake is less sensitive to rainfall variations showing 10% decrease in lake level despite 50% decrease in precipitation. Stegan et al. (2008) [7] applied a SWAT model for Lake Tana Basin to test the performance and feasibility for predicting the flow in the Lake. The model was calibrated and validated, resulting that the baseflow (40% - 60%) is an important component of the total discharge within the study area that contributes more than the surface runoff. More than 60% of the rainfall are lost in the watershed due evapotranspiration. The study of the water balance showed that the outflow of the lake was 4 billion m^3 which accepted compared to what was reported by Shahin (1985) [1] with 3.93 billion m^3. Mekonnen et al. (2018) [8] analyzed the effect of land use and land cover (LULC) changes and climate change on the streamflow for the whole upper Blue Nile River basin. Non-parametric Mann–Kendall statistics was used for statistical trend analysis, while the SWAT program was used for water balance modelling. Three different approaches were applied in this process; LULC, climate changes, and a combination of both changes. The approach of LULC change indicate that an increases in the cultivated land and decreases in the forest before 1995. Based on the effects of climate change only the surface run off and base flow were affected by the increase of rainfall intensity and number of extreme rainfalls. However, the results of the combined approach indicated that the mean annual streamflow increased by 16.9 % between the 1970s and 2000s. Kidane et al. (2018) [9] conducted a hydrological model using SWAT software to study the response of climate and land use/land cover (LULC) dynamics on Guder River which is a tributary of The Upper Blue Nile (Abbay) river, and the stream flow under different scenarios. The Landsat satellite imageries were obtained from Ethiopian Mapping Agency to identify the LULC of the watershed during three periods; 1973, 1995 and 2015. The SWAT model was calibrated using 1995 LULC and 1983–1991 climate data, and validated during the period 1992 to 1996. Study showed a change in the stream flow due to LULC change in the watershed for both rainy and dry seasons. In rainy seasons, an increase of about 8.49% and 14.50% was founded considering short rainy and wet season respectively. Whereas; the result also depicted that a decrease of 9.65%, in dry season, compared with 1973 LULC. As for the effect of climate change, a significant impact on the catchment during June to September (wet season), was found, where the stream flow was increased from 35.98 to 37.59 m3/s that account 4.46% rise because of above 40 years of local and global climate change. The simulated stream flow using 1973–1982 and 2006–2015 climate data was 2.89 m3/s and 2.76 m3/s respectively.

In spite of the importance of lake tana, as one of the main sources of the Blue Nile water, the previous studies are not sufficient to express such importance, especially the effect of LULC and climatic changes is accelerated in the few last years due to the global warming phenomena. Based on such a fact, the present work is interested by Studying the water balance of Lake Tana Basin using a SWAT model.

II. Objective

The main objective of this research was to develop a hydrological model to stimulate the Upper Blue Nile basin and provide predictions of the basin water balance. For this purpose, a Hydrological model was established using SWAT, and was calibrated and validated using SWAT-

CUP. In addition, the water balance components such as precipitation, run off, and evapotranspiration was examined. The outflow out of the lake was compared to Shahin (1985) [1].

III. Study Area

Lake Tana is the source of the Blue Nile River. The lake, at an elevation of about 1800 m, has a surface area of about 3000 km^2. Lake Tana basin includes more than 40 torrents discharge in Tana Lake. The major torrents are; Gilgel Abbay, Gumera, Ribb, and Megech. Such four torrents contribute more than 93% of the inflow to the Lake. The catchment area of the basin is approximately 15,000 Km2 and rises up to 4000 m a.s.l. at the northern part. Lake Tana presents the largest fresh water body in Ethiopia, it has a surface area of about 3000 km2 (J. V. Sutcliffe, 1999) [10]. The Lake located at 120 0`N latitude, 370 15`E longitude and altitude of 1781 m a.s.l. as shown in Fig. (2). The Lake has 84 Km maximum length, 64 Km width and 14 m depth (Shahin, 1985) [1]. The Blue Nile presents the only outflow from Lake Tana. The yearly outflow from Lake Tana is about 3.93 billion m^3. The area has a rainy season between June – September with average rainfall about 1300 mm. The mean annual evapotranspiration is about 773 mm. The lake itself considered shallow with a maximum depth of 15 m.

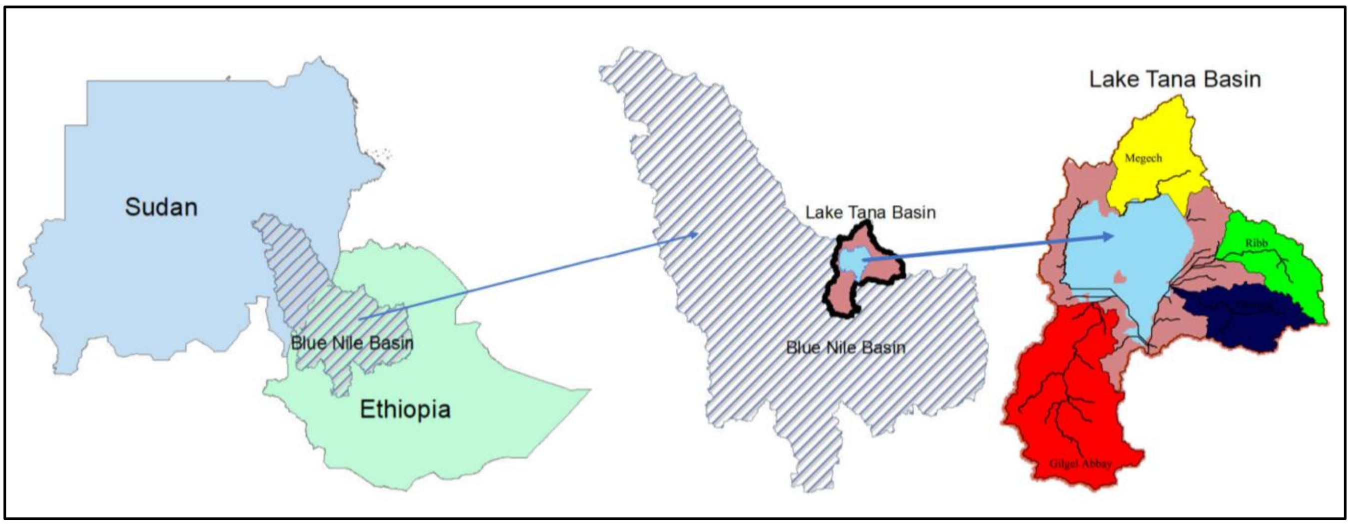

Fig. 2 Location of Lake Tana basin

IV. Input Data

The SWAT model required many input data such as Digital Elevation Model (DEM), Soil map, Land use land cover (LULC) and weather data to run the model and also required discharge observation for calibration and validation of the simulated model.

A. Digital Elevation Model

The DEM defines the terrain and the topography for the study area which insert to the SWAT to delineate the basin and generate the stream lines as shown in Fig (3). The present study provides the DEMs produced by ASTER Global Digital Elevation Model V003. The ASTER project is a joint endeavor by Japan's Ministry of Economy, Trade and Industry (METI) and the U.S. National Aeronautics and Space Administration (NASA).

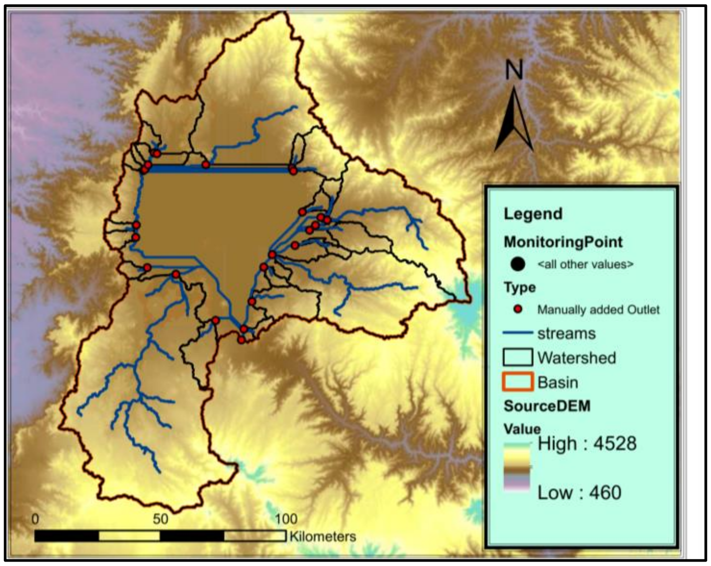

Fig. 3 Lake Tana Basin and delineated streams Digital Elevation Model

B. Soil Map

Soil map with soil data for the different layers of soil is obtained from the Food and Agriculture Organization of the united nation (FAO). The map scale is 1: 5000000 with about 4600 soil type. The SWAT model require the data in different properties such as; soil texture, available water content, hydraulic conductivity and organic carbon content for the different layers at each soil type. The soil map classes were converted to 6 classes in SWAT. The FAO digital soil map is available through the FAO site. Fig. (4) illustrates the major soils within the study area.

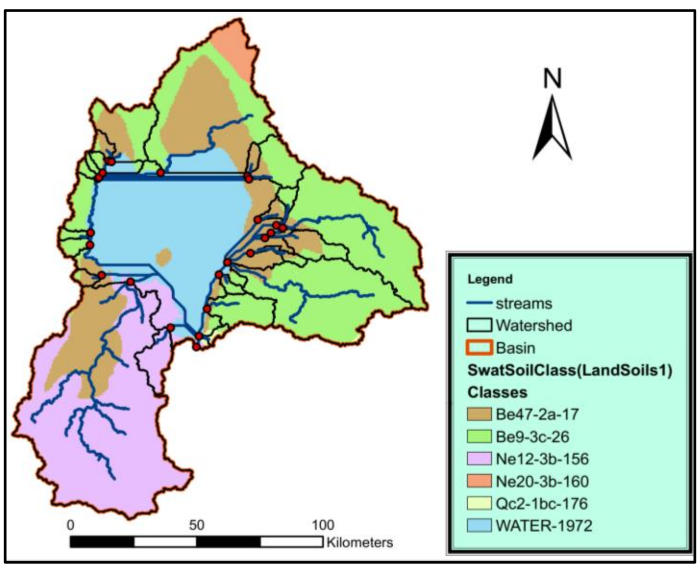

Fig. 4 FAO Soil Map of Lake Tana basin

C. Land use land cover Map

Land Use Land Cover (LULC) is considered the major factor which affect the run off, Evapotranspiration, and surface erosion in any basin. The data for the study area is obtained from the GIS portal of the International Livestock Research Institute (ILRI) with resolution 2200x2200 m. The map which covers the study area contains seven land cover types corresponding to the year 2004. The processed land cover data was linked to the database of SWAT using the seven categories; water body, agriculture area, Agropyron cristatum, Rangeland, wetland, Swamps and Forests as shown in Fig (5).

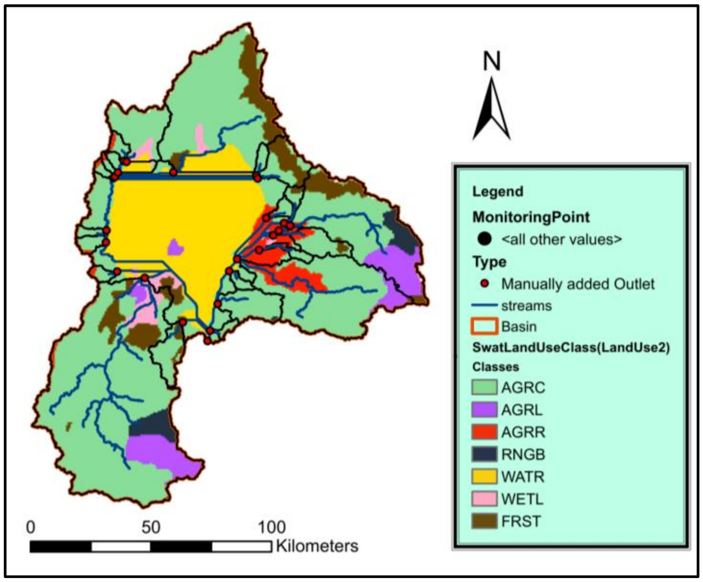

Fig. 5 ILIR Land use Land Cover Map of Lake Tana basin

D. Weather Data

The SWAT model outputs are affected by the weather data such as precipitation (mm), Wind (m/s), Temperature (c), relative humidity (fraction), and solar (MJ/m^2). Daily meteorological data required by SWAT were obtained for the period between 1978 – 2014 from Climate Forecast System Reanalysis (CFSR). The CFSR stations data can be downloaded from the Global Weather Data for SWAT site (https://globalweather.tamu.edu/) and Fig. (6) shows the station location.

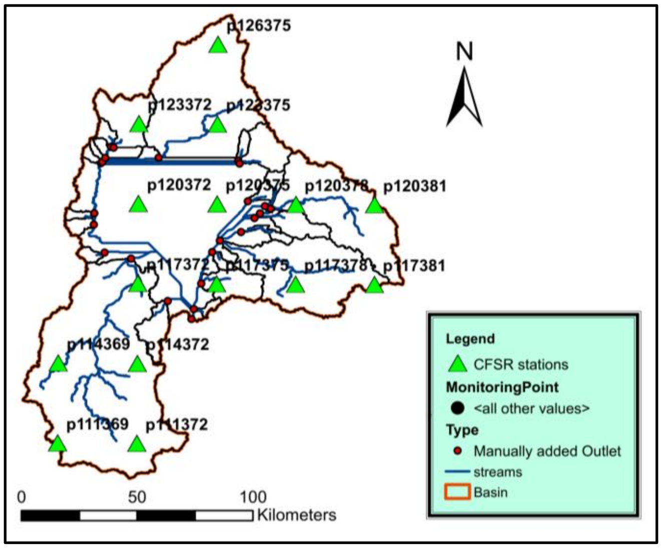

Fig. 6 Location of weather stations within Lake Tana Basin

E. Discharge Data

Discharge data (m^3/s) obtained for the Ribb river for the period 1992 -1996 for calibration and validation between 2004-2005 from master's Thesis "Investigation of Hydrologic Response Unit (HRU) Discretization for Erosion Modelling with SWAT in the Upper Blue Nile Basin" by Helena Huber [11]. The average monthly outflow at the Ribb river is given in Fig (7).

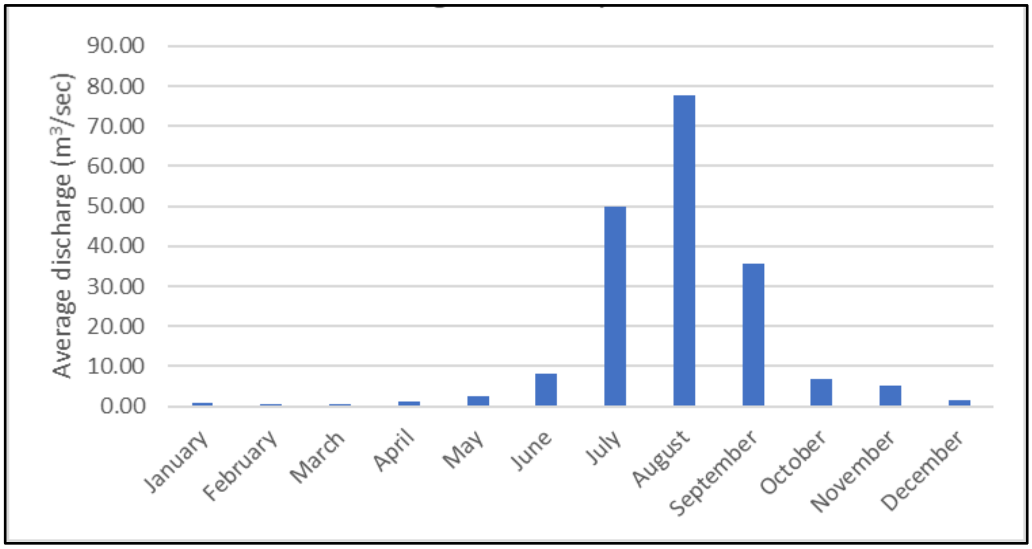

Fig. 7 Average monthly outflow for the Ribb river

V. Methodology

The present study applies the physically based watershed model SWAT in the Lake Tana basin to investigate the basin water balance under the influence of topographic, land use, soil and weather data. The application of the model involved calibration, uncertainty analysis, sensitivity and validation. First the simulation is done from 1979 to 2013 noting that there is a warm up period of 3 years in order to reach acceptable values for the model parameters. SWAT uses Spatial data to simulate water at a catchment on a yearly, monthly, or daily scale. SWAT uses Hydraulic Response Units (HRU) that divide the area according to the land use, soil and slope. The program calculates the water balance component based on the water balance equation (1)

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{qw} \right) \quad \text{.....................................(1)}$$

where

SW_t : Final soil water content (mm H_2O).
SW_0: Initial soil water content on day i (mm H_2O).
t: Time (days).
R_{day}: Precipitation on day i (mm H_2O).
Q_{surf}: Surface runoff on day i (mm H_2O).
E_a: Evapotranspiration on day i (mm H_2O).
w_{seep}: Water entering the vadose zone form the soil profile on day i (mm H_2O).

Q_{qw}: Return flow on day i (mm H_2O).

In the present model, the SCS curves are used. SWAT uses the precipitation input for simulation of surface runoff volumes and peak runoff rates at HRU scale. The SCS curve number equations are eq. (2) and (3).

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

$$S = 25.4 * (\frac{1000}{CN} - 10) \quad \text{.....(3)}$$

where

I_a : Initial abstractions (mm H_2O).
S: Retention parameter (mm H_2O).
CN: Curve number for the day.

The model was calibrated and validated using SWAT-CUP with two different algorithms Sequential Uncertainty Fitting version 2 (SUFI-2) and Generalized Likelihood Uncertainty Estimation (GLUE). SWAT-CUP uses the coefficient of determination (R^2) and Nash-Sutcliff Efficiency (NSE) to analyze the results and compare it with the observation data. The observation data for the Ribb used for calibration during 1992 to 1996. While the observation data used for validation during 2004 to2005. The regression equation which used to determine coefficient of determination and Nash-Sutcliff Efficiency between the observation data and the best simulation can be calculated by eq. (4) and eq. (5) respectively.

$$R^2 = \frac{\left[\sum_i (Q_{m,i} - \overline{Q_m})(Q_{s,i} - \overline{Q_s})\right]^2}{\sum_i (Q_{m,i} - \overline{Q_m})^2 \sum_i (Q_{s,i} - \overline{Q_s})^2} \quad \text{..... (4)}$$

where
R^2: Coefficient of determination.
Q: Variable (Discharge m^3/sec).
m: Measured data.
s: Simulated data.
i: The i^{th} measured or simulated data.

$$NSE = 1 - \frac{\sum_i (Q_m - \overline{Q_s})_i^2}{\sum_i (Q_m - \overline{Q_m})^2} \quad \text{..... (5)}$$

where
NSE: Nash-Sutcliffe Efficiency.
Q: Variable (Discharge m^3/sec).
m: Measured data.
s: Simulated data.
i: The i^{th} measured or simulated data.

Uncertainty analysis were tested using two methods; p-factor, and r-factor. P-factor is the percentage of measured data bracketed by the 95% prediction uncertainty (95PPU) which is calculated at the 2.5% and 97.5% levels of the cumulative distribution. The r-*factor* which is the average thickness of the 95PPU band divided by the standard deviation of the measured data defined in eq. (6), since,

$$r - \text{factor} = \frac{\text{p-factor}}{\sigma_{obs}} \quad \ldots\ldots(6)$$

where σ_{obs} is the Standard deviation of the measured data.

VI. Results and discussion

The analysis and discussion of the obtained results are arranged as follows:

A. Parameter sensitivity analysis

The parameters considered for calibration are SCS runoff curve number, Baseflow alpha factor (days), Groundwater delay (days), threshold depth of water in the shallow aquifer required for return flow to occur (mm), Soil evaporation compensation factor, Surface runoff lag time, Manning's "n" value for the main channel, Available water capacity of the soil layer, Saturated hydraulic conductivity, and Threshold depth of water in the shallow aquifer for "revap" to occur (mm). The calibration showed the most sensitive parameters as shown in Table (1) with their fitted value. The fitted parameters were inserted into the SWAT model to calibrate the study area and examine the water balance components extracted from the simulation.

Table (1) Calibrated set of parameters

Parameters	Type of change*	Fitted Parameters	
		SUFI-2	GLUE
CN2.mgt	R	-0.071	-0.011
ALPHA_BF.gw	V	0.72	0.87
GW_DELAY.gw	V	163.56	220.98
GWQMN.gw	A	2190	357.90
ESCO.bsn	V	0.63	0.32
SURLAG.bsn	V	4.79	11.85
CH_N2.rte	V	0.16	0.225
SOL_AWC(..).sol	R	0.081	0.097
SOL_K(..).sol	R	-0.037	0.24
REVAPMN.gw	V	0.039	0.078

The sign * denotes that; R is value from the SWAT database is multiplied by a given value, V is replace the initial parameter by the given value, and A is adding the given value to initial parameter value.

B. Model calibration and validation

SUFI-2 and GLUE methods were used for the calibration of the SWAT model in the Ribb river, then the fitted parameters were applied to the whole basin model. The calibration and validation for the model with both algorithms showed satisfactory results as shown in Table (2). The R^2 and NSE values exceeds 0.70 which categories the model performance as a good and acceptable model. For calibration, both methods have good agreement in dry season with the observation data, but in the wet season between July - September, SUFI-2 showed better results for the peaks outflow. Fig.(8) shows the time series of measured and calibrated monthly outflow at Ribb station during the calibration period. It is obvious that both the observed and calibrated discharges are close to each others for the calibration period. Only, the calibrated discharge in the year 1993 shows some deviation from the observed one which may refer to the inaccurate measurement or maybe subjected to dry season.

Table (2) Calibration and Validation results for the outflow at the Ribb

Objective Function		Calibration	Validation
NSE	SUFI-2	0.74	0.76
	GLUE	0.74	0.68
R^2	SUFI-3	0.74	0.8
	GLUE	0.75	0.79
p-factor	SUFI-4	79%	75%
	GLUE	70%	71%
r-factor	SUFI-5	1.17	1.08
	GLUE	0.97	1.39

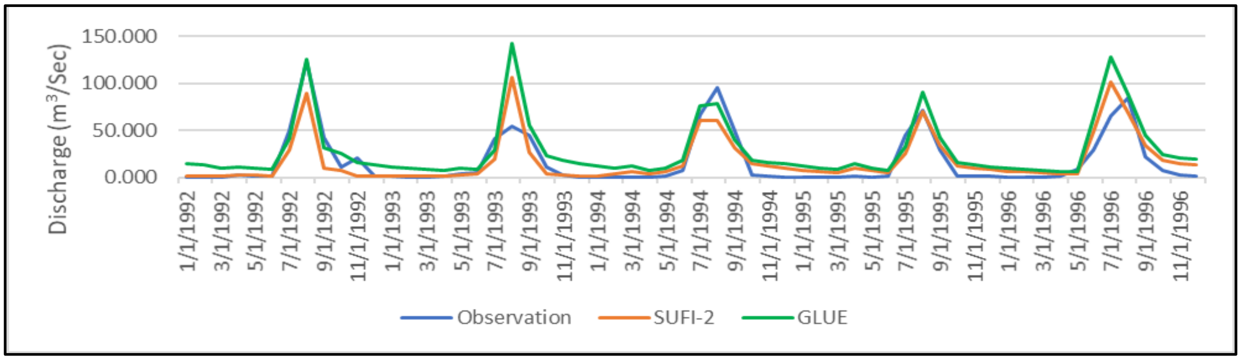

Fig. 8 **Observed and calibrated discharge in Ribb river for the calibration period (1992 – 1996)**

The validation results were better for the Ribb river using the SUFI-2 algorithm with higher values of R^2 and NSE as defined in table (2). AS indicated in Fig (9), the validated flow from SUFI-2 agrees well with the observation data in the wet season (July – September).

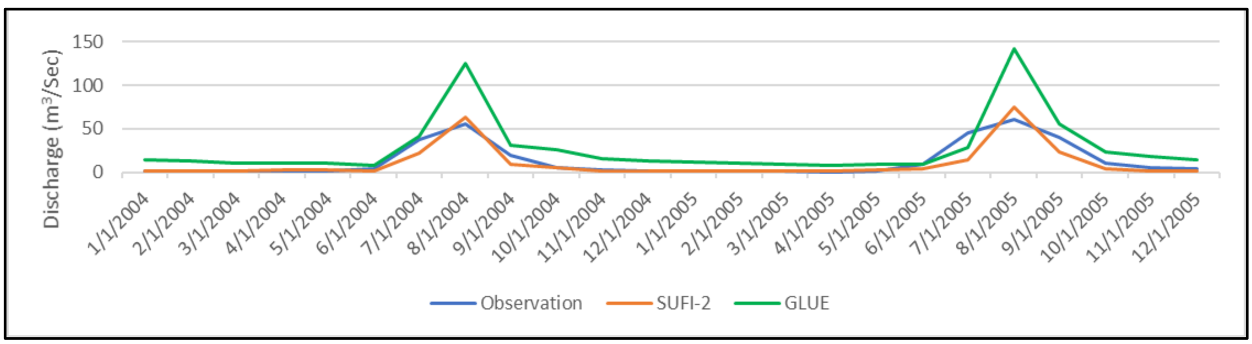

Fig. **9 Observed and validation discharge in Ribb river for the calibration period (2004 - 2005)**

C. Hydrological Water Balance

The main water balance components are; precipitation, Evapotranspiration, Surface runoff, Return Flow, Lateral Flow, percolation to shallow aquifer, and recharge to deep aquifer. The Average annual rates of the water balance components, for Lake Tana basin, are listed in table (3).

Table (3) Average annual rates of the water balance components for Lake Tana basin

Hydrologic Parameter	Rates, mm/year
Precipitation	1063
Evapotranspiration	933.2
Revap shallow aquifer	28.27
Surface Runoff	61.58
Return Flow	155.81
Lateral Flow	59
Percolation to shallow aquifer	262.1
Recharge to deep aquifer	13.11

The evapotranspiration losses address about 85% of the annual precipitation in the basin. The average annual evapotranspiration throughout Lake Tana basin is 933 mm while it is 1700 mm within the Lake itself since have large area with shallow depth. The surface runoff presents about 25% of the basin outflow while the other value goes to lateral flow and return flow. The outflow of the basin was calculated for the calibrated model and plotted as shown in Fig (10). The results indicated that there is increase in the outflow through for the years period 2011 to 2013.

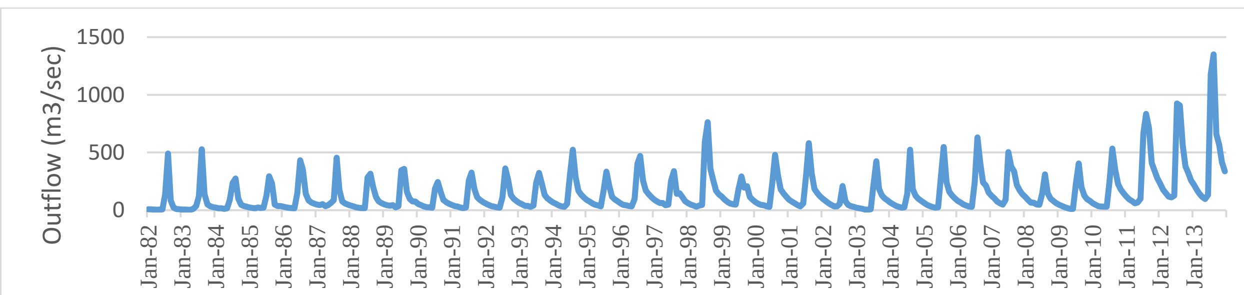

Fig. 10 Time series of Lake Tana basin outflow (1982-2013)

VII. Conclusion

Based on the above analysis and discussion of results, the main conclusions are given below.

1- A SWAT model is prepared and successfully calibrated and validated to study the water balance throughout Lake Tana basin.
2- The calibration and validation show acceptable results for outflow with NSE > 0.70 and $R^2 > 0.75$. Both SUFI-2 and GLUE gave satisfactory results for the outflow calibration with p-factor more than 70% and r-factor 0.97 for GLUE and 1.17 for SUFI-2. SUFI-2 showed better results for the peaks outflow.
3- The evapotranspiration losses address about 85% of the annual precipitation in the basin.
4- The average annual evapotranspiration throughout Lake Tana basin is 922 mm while it is 1700 mm within the Lake itself since have large area with shallow depth.
5- The surface runoff presents about 25% of the basin outflow while the other value goes to

lateral flow and return flow.

6- The outflow increases throughout the years period 2011 to 2013.
7- The outflow at the lake exit is about 4.47 billion m^3/year while it was 3.93 billion m^3 as reported by Shahin (1985) [1].
8- Although, the balance at the lake outlet shows deficiency in the water balance with about 27%, the outflow from the lake gives satisfactory results.

The developed model can be used for updated land use and land cover (LULC) maps to study the effect the LULC change on the Water balance of the basin. Due to the scarcity of the data in the basin and the complexity of the area, the basin needs more investigation.

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