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Discussions

Calibration and validation of SWAT model and estimation of water balance components of Shaya mountainous watershed, Southeastern Ethiopia

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Abstract

To utilize water resources in a sustainable manner, it is necessary to understand the quantity and quality in space and time. This study was initiated to evaluate the performance and applicability of the physically based Soil and Water Assessment Tool (SWAT) model in analyzing the influence of hydrologic parameters on the streamflow variability and estimation of monthly and seasonal water yield at the outlet of Shaya mountainous watershed. The calibrated SWAT model performed well for simulation of monthly streamflow. Statistical model performance measures, coefficient of determination (r^2) of 0.71, the Nash–Sutcliffe simulation efficiency (E_{NS}) of 0.71 and percent difference (D) of 3.69, for calibration and 0.76, 0.75 and 3.30, respectively for validation, indicated good performance of the model simulation on monthly time step. Mean monthly and annual water yield simulated with the calibrated model were found to be 25.8 mm and 309.0 mm, respectively. Overall, the model demonstrated good performance in capturing the patterns and trend of the observed flow series, which confirmed the appropriateness of the model for future scenario simulation. Therefore, SWAT model can be taken as a potential tool for simulation of the hydrology of unguaged watershed in mountainous areas, which behave hydro-meteorologically similar with Shaya watershed. Future studies on Shaya watershed modeling should address the issues related to water quality and evaluate best management practices.

1 Introduction

Understandings on hydrological processes to develop suitable models for a watershed are the most important aspect in water resource development and management programmes. Water resource development is the basic and crucial infrastructure for a nation's sustainable development. To utilize water in a sustainable manner, it is necessary to understand the quantity and quality in space and time through studies and researches (McCornick et al., 2003). Major hydrological processes can be quantified with the help of water balance equations. The component of water balance of a watershed is influenced by climate, and the geophysical characteristics of the watershed such as topography, land use and soil. Consideration of the relationship between these physical parameters and hydrological components is very essential for any water resource development related work (Sathian and Symala, 2009). Since the hydrologic processes are very complex, their proper comprehension is essential and therefore, watershed based hydrological models are widely used.

Mountainous watersheds are the origin of many of the largest rivers in the world and represent major sources of water availability for many countries (Sanjay et al., 2010). They represent not only local water resources but also considerably influence the runoff regime of the downstream rivers. Farm Africa-SOS Sahel Ethiopia (2007), described that the Bale Mountain National Park (BMNP) is a source of over 40 streams on which more than 12 million people are dependent. The importance of the hydrological services that the area provides to south-eastern Ethiopia and parts of Somalia and Kenya have gradually been recognized over the subsequent years and their conservation is now a primary purpose of the park. Shaya is one of a river which originates from afroalpine area of the BMNP among many other rivers. Expansion and encroachments of agriculture, settlements and livestock, however, are the main causes that make the hydrological system of the area in under continuous transformation.

At the downstream parts of the river, there are different water based projects which are attached to the flow of Shaya River. The projects include existing and proposed irrigation schemes, tourism and fish farming at different parts of the river. Hence, estimation of monthly, seasonal and long term runoff yield helps to identify the best and sustainable land use and management options in the area. Therefore, the output of this study can be taken as an input to plan and implement effective land and water resources development and management.

There are a number of integrated physically based distributed models. Among which, researchers have identified SWAT as one of the most promising and computationally efficient model (Arnold et al., 1998; Neitsch et al., 2005; Gassman et al., 2007).

Therefore, to test the capability of the model in determining the effect of spatial variability of the watershed on streamflow, SWAT 2005 with ArcGIS interface was selected. The time series data on climate and runoff yield were available at the gauging stations of the watershed and these were used to calibrate and validate the SWAT model and to assess its applicability in simulating runoff yield from the Shaya watershed. The objective of this study was to perform calibration and validation of SWAT model at the outlet of Shaya watershed in the Bale Mountainous area and to estimate water balance components of the watershed.

2 Materials and methods

2.1 Description of the study watershed

Shaya watershed is found in south-eastern part of Ethiopia in Genale-Dawa basin at the upper most parts of the Weyb basin, located between 6° 52′–7° 15′ N latitudes and 39° 46′–40° 02′ E longitudes as shown in Fig. 1. It covers a total drainage area of 503.5 km^2. The Shaya River originates from the northern flanks of the Bale Mountains and first flows generally north-eastwards before joining the Weyb river which flows to east and south eastwards for the remainder of its course. Finally, it joins with Genale and Dawa River near Ethiopia–Somalia border to strengthen its journey to Somali lowlands. It originates from an elevation of 4343 m a.s.l., in the Bale Mountains extreme point locally called Sanetti plateau to an elevation of 2357 m a.s.l at the outlet of the watershed. The average areal annual rainfall distribution is 1071 mm and the annual maximum and minimum temperature of the watershed area is about 19.7 °C and 6.1 °C, respectively.

The Shaya river watershed is a region of rich environmental diversity, but with increasing levels of environmental stress in recent years from a rapidly expanding human population (Farm Africa-SOS Sahel Ethiopia, 2007).

2.2 General description of SWAT model

SWAT is the acronym for Soil and Water Assessment Tool, a river basin scale, continuous-time and spatially distributed model developed for the USDA Agricultural Research Service (ARS). It was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch et al., 2005). In recent years, SWAT model has gained international acceptance as a robust interdisciplinary watershed modeling. SWAT is currently applied worldwide and considered as a versatile model that can be used to integrate multiple environmental processes, which support more effective watershed management and the development of better informed policy decision (Gassman et al., 2007). The review of SWAT model applicability to Ethiopian situations at relatively larger watersheds (Dilnesaw, 2006; Setegn, 2010) indicated that the model is capable of simulating hydrological processes with a reasonable accuracy. In SWAT, a watershed is divided into multiple sub-watersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics (Neitsch et al., 2005). In the land phase of hydrological cycle, SWAT simulates the hydrological cycle based on the water balance equation:

$$\mathrm{SW}_t = \mathrm{SW}_\mathrm{o} + \sum_{i=1}^{t} \left(R_\mathrm{day} - Q_\mathrm{surf} - E_\mathrm{a} - W_\mathrm{seep} - Q_\mathrm{gw}\right) \tag{1}$$

where, SW_t is the final soil water content (mm), SW_o is the initial soil water content on day i (mm), t is the time (days), R_day is the amount of precipitation on day i (mm), Q_surf is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_seep is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_gw is the amount of return flow on day i (mm).

The SCS (Soil Conservation Service) curve number procedure (USDA-SCS, 1972) method was used for estimating surface runoff using daily rainfall, SWAT simulates

surface runoff volumes and peak runoff rates for each HRU. In this study, the SCS curve number method was used to estimate surface runoff. The SCS curve number equation is:

$$Q_\mathrm{surf} = \frac{(R_\mathrm{day} - 0.2S)^2}{(R_\mathrm{day} + 0.8S)} \tag{2}$$

where, Q_surf is the accumulated runoff or rainfall excess (mm), R_day is the rainfall depth for the day (mm), S is the retention parameter (mm).

SCS defines three antecedent moisture conditions: I – dry (wilting point), II – average moisture and III – wet (field capacity). The moisture condition I curve number is the lowest value the daily curve number can assume in dry conditions. The curve numbers for moisture conditions I and III are calculated with the Eqs. (3) and (4), respectively.

$$\mathrm{CN}_1 = \mathrm{CN}_2 - \frac{20 \times (100 - \mathrm{CN}_2)}{(100 - \mathrm{CN}_2 + \exp[2.533 - 0.0636 \times (100 - \mathrm{CN}_2)])} \tag{3}$$

$$\mathrm{CN}_3 = \mathrm{CN}_2 \times \exp[0.00673(100 - \mathrm{CN}_2)] \tag{4}$$

where CN_1 is the moisture condition I curve number, CN_2 is the moisture condition II curve number, and CN_3 is the moisture condition III curve number. The retention parameter is defined by Eq. (5)

$$S = 25.4\left(\frac{1000}{\mathrm{CN}} - 10\right) \tag{5}$$

2.3 SWAT model inputs

2.3.1 Digital Elevation Model (DEM)

The DEM forms the base to delineate the watershed boundary, stream network and create sub-basins. This was performed by the pre-processing module of the SWAT but requires a so-called minimum threshold area. Topography was defined by a DEM which describes the elevation of any point in a given area at a specific spatial resolution as a digital file. It was also used to analyze the drainage patterns of the land surface terrain. And sub-basin parameters such as slope, slope length, and defining of the stream network with its characteristics such as channel slope, length, and width were derived from the DEM. For this specific study a DEM with a resolution of 30 m was used, which was sourced from ASTER GDEM official website.

2.3.2 Soil properties

Soils in the study watershed are classified on the basis of the revised FAO/UNESCO-ISWC (FAO/UNESCO-ISWC, 1998) classification system. The soil data was extracted from the 1 : 250 000 scale of soil map (Fig. 2) developed by Ministry of Water and Energy (MoWE) (MoWE, 2007). Basic physico-chemical properties of major soil types in the watershed were mainly obtained from the following sources: Genale-Dawa river basin integrated resources master plan, Soil database and digital soil map from the MoWE produced between the year 2004 and 2007; Soil and Terrain Database for north-eastern Africa CD-ROM (FAO, 1998). In addition to these sources, some soil properties were estimated based on available soil parameters.

2.3.3 Land Use and Land Cover (LULC) data

The LULC map and all datasets were obtained from (MoWE, 2007). This spatial database was derived from satellite imagery and field data collected between year 2004 to 2007 (MoWE, 2007) and is the most current and detailed LULC data known to be available for the study watershed (Fig. 2). The reclassification of the land use map was made to represent the land use according to the specific LULC types and the respective crop parameter for SWAT database. A lookup table that identifies the SWAT land use code for the different categories of LULC was prepared so as to relate the grid values to SWAT LULC classes.

2.3.4 Meteorological data

The SWAT model requires daily meteorological data that could either be read from a measured data set or be generated by a weather generator model which include precipitation, maximum and minimum air temperature, solar radiation, wind speed and relative humidity. Meteorological data collected from National Meteorological Service Agency of Ethiopia (NMSA) for Bale Robe, Dinsho, Agarfa, and Goba stations are within the watershed and some are in the vicinity of watershed boundary as shown in Fig. 1. The SWAT weather generator model WXGEN was used to fill missing values in weather data. The Penman–Montheith method which utilizes the solar radiation, relative humidity and wind speed data records was employed for estimation of potential evapotranspiration (PET) for this specific study. Meteorological stations were geo-referenced using latitude, longitude, and elevation data.

The typical quality of rainfall data was checked by cross correlation between the stations. The correlation coefficient among the stations on monthly rainfall amount ranged from 0.91 to 0.97. This implied a good agreement or consistency of data record on the monthly rainfall series of the gauging stations. The climate data for study periods were finally prepared in .dbf format and imported to the SWAT model database. Mean monthly rainfall data followed more or less similar trend and patterns as shown on Fig. 3.

2.3.5 Hydrological data

The hydrology of the watershed reflects the rainfall pattern with river flow peaking firstly in April to May and subsequently in August and October. Daily river discharge data of the Shaya River was obtained from the Hydrology Department of the MoWE. It was used for performing sensitivity analysis, calibration and validation of the SWAT model.

An automated baseflow separation and recession analysis technique (Arnold et al., 1999) was employed to separate the baseflow and surface runoff from the total daily streamflow records. This information was then used in order to get SWAT to correctly reflect basic observed water balance of the watershed.

2.4 Model set up

2.4.1 Watershed delineation

The first step in creating SWAT model input is delineation of the watershed from a DEM. Inputs entered into the SWAT model were organized to have spatial characteristics. Before going in hand with spatial input data i.e. the soil map, LULC map and the DEM were projected into the same projection called UTM Zone 37N, which is a projection parameters for Ethiopia. A watershed was partitioned into a number of sub-basins, for modeling purposes. The watershed delineation process include five major steps, DEM setup, stream definition, outlet and inlet definition, watershed outlets selection and definition and calculation of sub-basin parameters. For the stream definition the threshold based stream definition option was used to define the minimum size of the sub-basins.

2.4.2 Hydrological Response Units (HRUs)

The land area in a sub-basin was divided into HRUs. The HRU analysis tool in ArcSWAT helped to load land use, soil layers and slope map to the project. The delineated watershed by ArcSWAT and the prepared land use and soil layers were overlapped 100 %. HRU analysis in SWAT includes divisions of HRUs by slope classes in addition to land use and soils. The multiple slope option (an option which considers different slope classes for HRU definition) was selected. The LULC, soil and slope map was reclassified in order to correspond with the parameters in the SWAT database. After reclassifying the land use, soil and slope in SWAT database, all these physical properties were made to be overlaid for HRU definition. For this specific study a 5 % threshold

value for land use, 20 % for soil and 20 % for slope were used. The HRU distribution in this study was determined by assigning multiple HRU to each sub-basin.

2.4.3 Sensitivity analysis

After a thorough preprocessing of the required input for SWAT model, flow simulation was performed for an eight years of recording periods starting from 1992 through 1999. The first three years of which was used as a warm up period and the simulation was then used for sensitivity analysis of hydrologic parameters and for calibration of the model. The sensitivity analysis was made using a built-in SWAT sensitivity analysis tool that uses the Latin Hypercube One-factor-At-a-Time (LH-OAT) (Van Griensven, 2005).

2.4.4 Calibration

Manual and automatic calibration method were applied. First the parameters were manually calibrated for the period of 1995 to 1999 until the model simulation results were acceptable as per the model performance measures. Next, the final parameter values that were manually calibrated were used as the initial values for the autocalibration procedure. The graphical and statistical approaches were used to evaluate the SWAT model performance a number of times until the acceptable values were obtained for surface runoff and baseflow independently. The flow calibration procedure made by SWAT developers in Santhi et al. (2001) and Neitsch et al. (2005) was carefully followed. SWAT developers assumed an acceptable calibration for hydrology at a $D \leq 15\,\%$, $r^2 > 0.6$ and $E_{\mathrm{NS}} > 0.5$ (Santhi et al., 2001; Moriasi et al., 2007).

2.4.5 Validation

Streamflow data of three years from 2003 to 2005 were used for validation. The three statistical model performance measures used in calibration procedure were also used in validating streamflow.

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2.4.6 Model performance evaluation

The regression coefficient (r^2) 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 flow and is calculated as follow:

$$r^2 = \frac{\left(\sum\left[X_i - X_{av}\right]\left[Y_i - Y_{av}\right]\right)^2}{\sum\left[X_i - X_{av}\right]^2 \sum\left[Y_i - Y_{av}\right]^2} \tag{6}$$

where: X_i is measured value, X_{av} is average measured value, Y_i is simulated value, Y_{av} is average simulated value, the same holds true for Eqs. (7) and (8).

Nash and Sutcliffe simulation efficiency (E_{NS}) indicates the degree of fitness of observed and simulated data and given by the following formula.

$$E_{NS} = 1 - \frac{\sum(X_i - Y_i)^2}{\sum(X_i - X_{av})^2} \tag{7}$$

The value of E_{NS} ranges from 1 (best) to negative infinity. If the measured value is the same as all predictions, E_{NS} is 1. If the E_{NS} is between 0 and 1, it indicates deviations between measured and predicted values. If E_{NS} is negative, predictions are very poor, and the average value of output is a better estimate than the model prediction (Nash and Sutcliffe, 1970).

The percent difference (D) measures the average difference between the simulated and measured values for a given quantity over a specified period were calculated as follows:

$$D = 100\left(\frac{\sum Y_i - \sum X_i}{\sum X_i}\right) \tag{8}$$

A value close to 0 % is best for D. However, higher values for D are acceptable if the accuracy in which the observed data gathered is relatively poor.

3 Results and discussions

3.1 Sensitivity analysis

The model considered twenty seven flow parameters for sensitivity analysis from which twenty one of them were found to be relatively sensitive with the category of sensitivity ranging from very high to small. Among the sensitive flow parameters the ground water parameters were found to be more sensitive to streamflow. Deep aquifer percolation fraction; Rchrg_Dp, Initial curve number (II) value; Cn2, Baseflow alpha factor [days]; Alpha_Bf, Threshold water depth in the shallow aquifer for flow [mm]; Gwqmn, Soil evaporation compensation factor; Esco, Soil depth [mm]; Sol_Z, Threshold water depth in the shallow aquifer for "revap" [mm]; Revapmin, Maximum potential leaf area index; Blai, Available water capacity [(mm water) (mm soil)$^{-1}$]; Sol_Awc, Maximum canopy storage [mm]; Canmx, Groundwater Delay [days]; Gw_Delay, Saturated hydraulic conductivity [mm h^{-1}]; Sol_K and Surface runoff lag time [days]; Surlag were found to be the most effective hydrologic parameters for the simulation of streamflow. A brief description of each hydrologic parameter is listed in the SWAT model user's manual (Neitsch et al., 2005).

3.2 Model calibration

Model calibration followed sensitivity analysis. Calibration for water balance and streamflow was first done for average annual conditions. After the model was calibrated for average annual conditions, we shifted into monthly and daily records to fine-tune the calibration processes. Model efficiency measures for initial monthly default simulation r^2, E_{NS} and D were 0.60, 0.16 and 96.6 respectively which were beyond the acceptable ranges. Thus, model parameter adjustments were undertaken for a realistic hydrologic simulation.

The baseflow separation technique indicated about 60 % of the total water yield was contributed from the subsurface water source which was more than surface runoff involvement for the total water yield at the outlet of the watershed.

The calibration processes were considered 13 most sensitive flow parameters (Table 1) and their values were varied iteratively within the allowable ranges until satisfactory agreement between measured and simulated streamflow was obtained. The autocalibration processes significantly improved model efficiency. The result from different statistical method of model performance evaluation met the criteria of $E_{NS} > 0.5$, $r^2 > 0.6$ and $D \leq \pm 15\%$. The statistical results of the model performance for both calibration and validation periods on monthly time steps are summarized in Table 2.

A rigorous hydrologic calibration resulted good SWAT predictive efficiency at the monthly time step of the watershed when compared to measured flow data (Fig. 4). The hydrograph of observed and simulated flow indicated that the SWAT model is capable of simulating the hydrology of Shaya mountainous watershed. However, the model was unable to capture some extreme values mainly, observed discharge on the month of November 1997 and October 1998. The under prediction of flow during peak events by the SWAT model has been reported in many studies (Thripati et al., 2003; Gassman et al., 2007; Sathian and Symala, 2009).

3.3 Model validation

It was found that the model has strong predictive capability with r^2, E_{NS} and D values of 0.76, 0.75 and 3.30, respectively. Statistical model efficiency criteria fulfilled the requirement of $r^2 > 0.6$ and $E_{NS} > 0.5$ which is recommended by SWAT developer (Santhi et al., 2001). This showed the model parameters represent the processes occurring in the watershed to the best of their ability given available data and may be used to predict watershed response for various outputs. The model validation results for monthly flow (Fig. 5) indicated generally a good fit between measured and simulated output. Since the model performed as well in the validation period, as for the calibration period hence,

the set of optimized parameters listed in Table 1 during calibration process for Shaya watershed can be taken as the representative set of parameters for the watershed.

3.4 Monthly and seasonal water yield simulation

The water yield was simulated for the base period of twelve years 1995 to 2006 on monthly time step at the outlet of Shaya watershed. Moreover, the result was summarized in a monthly and seasonal bases as comparatively dry (February–May), wet (June–September), intermediate (October–January) and annual bases, after an intensive model calibration for a sensitive flow parameters. Mean monthly and annual water yield simulated for a base period found to be 25.8 mm and 309.0 mm, respectively. Seasonal water yield simulation resulted 56.6 mm, 89.7 mm and 155.0 mm for dry, intermediate and wet seasons respectively. It indicated that the south-western part of the watershed has a larger contribution to the total water yield of the watershed.

3.5 Average annual water balance components of the watershed

The SWAT model estimated other relevant water balance components in addition to the daily and monthly discharge of the watershed. Average annual basin values for different water balance components during a base simulation periods shows average annual watershed gain and losses with change in soil water storage Table 3. From these components actual evapotranspiration contributed a larger amount of water loss from the watershed and total water yield is the amount of streamflow leaving the outlet of watershed during the time step.

4 Conclusion

Understandings on hydrological processes and develop suitable models for a watershed is the most important aspect in water resource development and management programmes. Watershed based hydrologic simulation models are likely to be used for the assessment of the quantity and quality of water. The performance and applicability of SWAT model was successfully evaluated through sensitivity analysis, model calibration and validation. Subsurface flow parameters were found to be more sensitive to the streamflow of the watershed, signifying the watershed is rich in ground water as a result of good recharge capacity. SWAT model was found to produce a reliable estimate of monthly runoff for Shaya watershed which was confirmed by various model efficiency measures. Therefore, the calibrated parameter values can be considered for further hydrologic simulation of the watershed. The model can also be taken as a potential tool for simulation of the hydrology of unguaged watershed in mountainous areas, which behave hydro-meteorologically similar with Shaya watershed. However, for a more accurate modeling of hydrology, a large effort will be required to improve the quality of available input data. Future studies on Shaya watershed modeling should address the issues related to water quality and evaluate best management practices to address different watershed management issues.

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Table 1. Finally calibrated flow parameter values and variation methods.

Flow parameters	Lower and upper bounds	Fitted values
Baseflow alpha factor [days]; Alpha_Bf	0.0 to 1.0	0.96
Maximum potential leaf area index; Blai	0.0 to 1.0	0.27
Maximum canopy storage [mm]; Canmx	0.0 to 10.0	7.55
Initial curve number (II) value; Cn2	±25.0	−15.90
Soil evaporation compensation factor; Esco	0.0 to 1.0	0.16
Groundwater delay [days]; Gw_Delay	±10.0	5.47
Threshold water depth in the shallow aquifer for flow [mm]; Gwqmn	±1000.0	854.02
Threshold water depth in the shallow aquifer for "revap" [mm]; Revapmin	±100.0	92.71
Deep aquifer percolation fraction; Rchrg_DP	0.0 to 1.0	0.48
Available water capacity [(mm water) (mm soil)$^{-1}$]; Sol_Awc	±25.0	15.43
Saturated hydraulic conductivity [mm h^{-1}]; Sol_K	±25.0	21.66
Surface runoff lag time [days]; Surlag	0.0 to 10.0	5.09

Table 2. Summary of model performance for calibration and validation periods.

	Mean annual water yield (mm)		Monthly model efficiency measures		
Period	Observed	Simulated	r^2	E_{NS}	D (%)
Calibration	330.30	336.09	0.71	0.71	3.69
Validation	251.89	319.87	0.76	0.75	3.30

Table 3. Average annual water balances simulated for a base periods of 1995–2006.

Water Balance Components	Amount (mm)
Precipitation; Precip	1028.80
Surface runoff ; Sur_Q	83.24
Lateral soil flow contribution; Lat_Q	13.56
Ground water contribution to streamflow; Gw_Q	212.46
Revap or shallow aquifer recharges	20.56
Deep Aquifer Recharges	174.12
Total water yield; Twyld	309.03
Percolation out of soil; Perc	435.80
Actual evapotranspiration; ET	518.7
Potential evapotranspiration; PET	606.8
Transmission losses; Tloss	0.22
Change in soil water storage	5.94

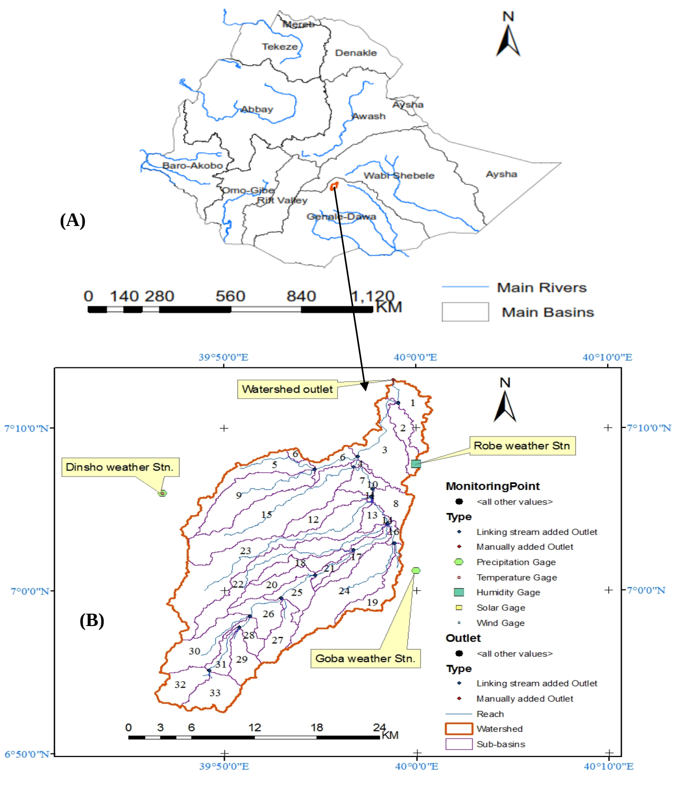

Fig. 1. Major river basins of Ethiopia **(A)**, and Sub-basins of Shaya watershed **(B)**.

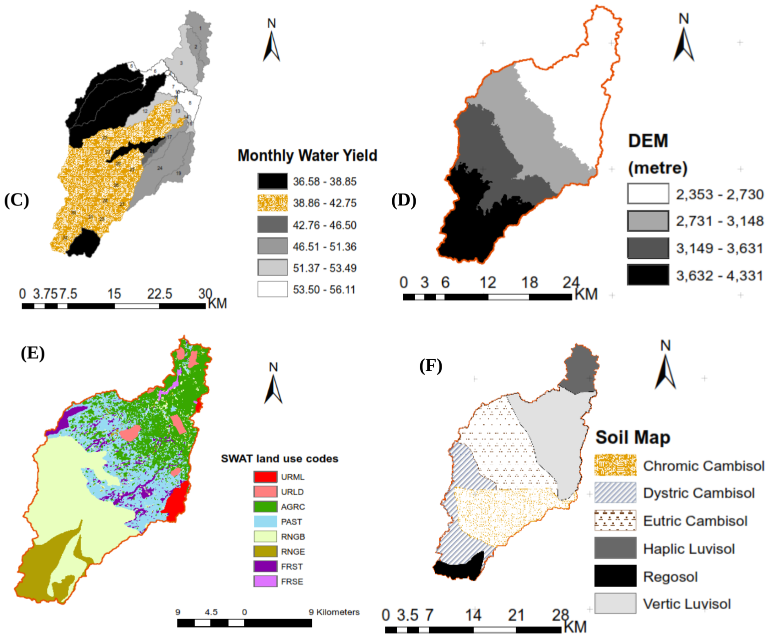

Fig. 2. Mean monthly water yield in mm **(C)**, Digital elevation model/DEM **(D)**, Land cover **(E)** and Soil map of Shaya watershed **(F)**.

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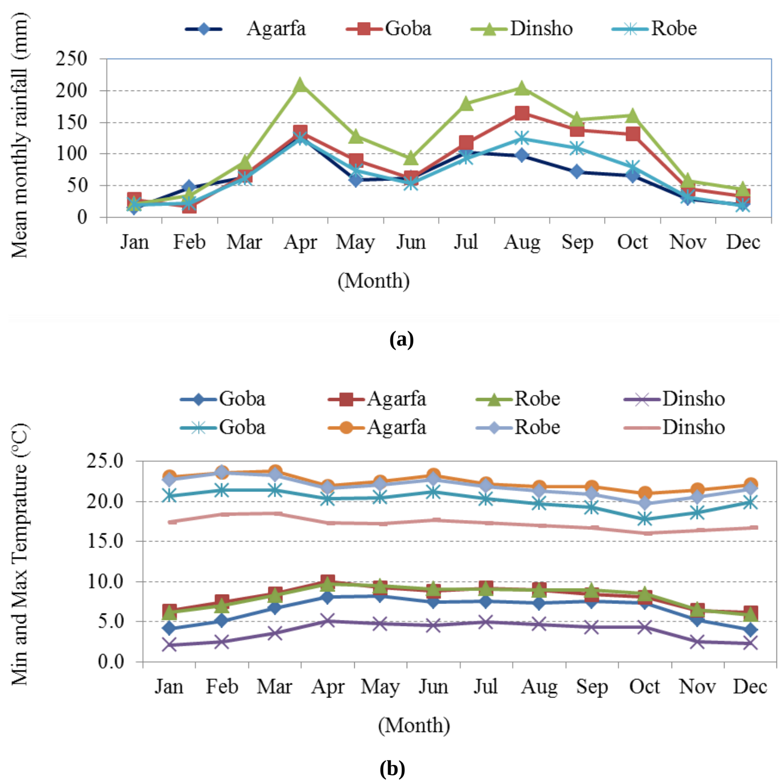

Fig. 3. Average monthly rainfall **(a)** and, Min. and Max. temperature **(b)** distributions.

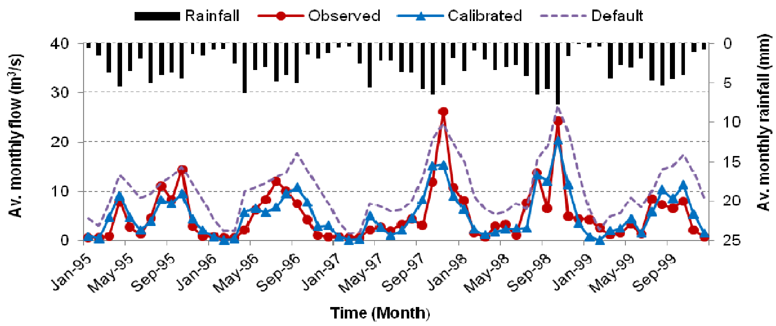

Fig. 4. Hydrograph of the observed, calibrated and default simulated monthly flow for the calibration period.

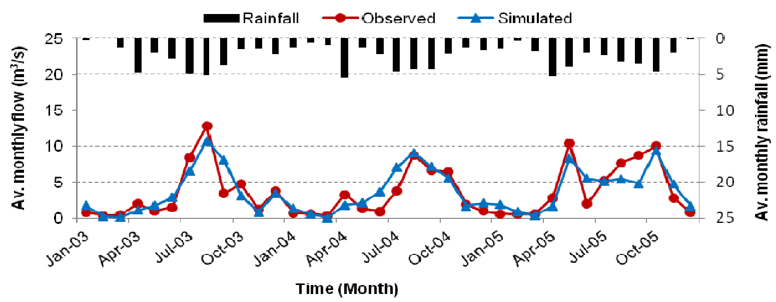

Fig. 5. Hydrograph of the observed and simulated monthly flow for the validation period.

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