Rainfall-Runoff Simulation using Remote Sensing and GIS Tool (SWAT Model) (A Case Study: Xebanghieng Basin in Lao PDR)

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Abstract
The Arc-SWAT model was applied to the Xebanghieng (XB) river Basin for modeling of the hydrological water balance. The primary objective of this study was to assess the water availability in the basin and feasibility of the SWAT model for prediction of main stream flow which is available for gauging site and which is not available so far for gauging site in the Basin. The water balance modeling was performed on annual, monthly and daily basis using spatial and temporal data of surface runoff. The model was calibrated and validated in main stream in lower part of XB River using SUFI-2. The sensitive analysis of the model to sub basin delineation and HRU(hydrologic response unit) definition thresholds showed that the flow is more sensitive to the HRU definition thresholds than sub basin discretization effect. SUFI-2 gave good result during calibration period. Coefficient of determination (R^2) criterion, Nash and Sutcliffe efficiency (NSE) were adopted to see performance of the model during calibration and validation period. Study indicated that due to high intensity of precipitation and good water retention capacity, the study area has high potential for agricultural activities.
Keywords: Xebanghieng River, GIS, SWAT, Runoff

Introduction

The quantity and rate of runoff is required for planning and management of water resources in scientific manner, because social activities have resulted increased and diversified demand of water in the basin. Due to human activities like urbanization, increase in population etc. in the catchment, discharge of the springs and streams are reducing day by day. The use of water, land, forest and related natural resources for economic development are un-sustainable due to poor management and inadequate practice. The Xebanghieng River basin is a sub basin of the Mekong River basin. The existing land and water resources system of the area is adversely affected by the rapid growth of population, deforestation, surface erosion and currently river supplies water to irrigated area of approximately 90,000-100,000ha. In dry season with the capacity to increase in the future and during dry season water resources availability is less in both main stream and tributaries, as a result severe drought is seen in the region. There is a need for runoff simulate of the Xebanghieng Basin that can support improved basin management programs that can better safeguard the alarmingly degradation of soil and water resources in Lao PDR. Reliable predictions of the quantity and rate of runoff from land surface into streams, rivers and water bodies are needed to support decision makers in developing watershed management plans for better soil and water conservation measures (Setegn, 2011) and to access potential future implications due to drivers of change. For such purpose, many of these models share a common base in their attempt to incorporate the heterogeneity of the watershed and spatial distribution of topography, vegetation, land use, soil characteristics, rainfall and evaporation. Some of the watershed models developed in the last two decades are CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) [1], EPIC - Erosion Productivity Impact Calculator [2], AGNPS (Agricultural None Point Source model) [3], SWAT (Soil and Water Assessment Tool) [4] and HSPF (Hydrologic Simulation Program Fortran) [5]. Many of these watershed models are applied for runoff and soil loss prediction. Simulation of runoff from a catchment can be carried out with the help of mathematical models. In this study, Arc SWAT is used for simulation of Runoff. Arc SWAT model is frequently used to simulate the runoff as suggested by Zhu Xingjun, Wang Zhoggen, Li Jiaxin,Yu Lei, Wang Jingui. Digital Elevation Model (DEM), Landuse/Land cover map, Soil map and topography of the study watershed are all spatial inputs required for the model. Another inputs required for the model are long term weather data, soil properties and Discharge data. Several available mathematical models (SWAT) could be used as analysis point of view.

In this study, authors attempt to simulate the quantity and rate of runoff from the Xebanghieng basin, which involves both available gauging site and un-gauge site in the basin using SWAT model which focus on calibration, validation, evaluation and application of SWAT model. The main objective of this study was to test the performance and feasibility of the SWAT model for prediction of stream flow in the Xebanghieng Basin.

There are few applications of SWAT model to Lao PDR conditions in relatively small watershed areas. The present study considers large scale application of the model on a watershed where most of the topographic features have slopes greater than 5%. For estimation of curve number to slopes above 5% an equation developed by reference [1] was used. Many distributed watershed models use different factors and parameters for the simulation of the hydrological processes. Hence it is important for these models to pass careful calibration tests and uncertainty analysis. In this paper application of SUFI-2 calibrations and uncertainty algorithms are discussed.

Study Area

The Xebanghieng River basin is a sub basin of the Mekong River basin. It is one of the largest basin in Lao PDR, which is located in the southern part of People Democratic Republic of Laos (Figure 1). The studied basin lies within 15˚50'0" -17˚10'0"N and 105˚10'0" -107˚10'0"E and encompasses a total area of 19939.59km^2. The main river of the Xebanghieng Catchment having a total length of 240.5 km. The elevation of the basin ranges from 34 m above mean sea level at its lowest point to 2491 m at its highest point. The general slope of the land in basin is downhill from east to west. The climate in the study area is characterized by two distinct seasons: The rainy season in the area has duration of five months (May-September) and provides for 87% of total annual rainfall. The dry season lasts seven month (October-April); especially there is almost no rain in November-January. The annual mean temperature ranges from 20 to 26˚C. Upper part is having sources of water and large middle part is suitable for agriculture and lower part is suitable for farm rice because of availability of irrigation. But during the dry season water resources availability is less, Paddy field is the dominant land cover in the basin, which is nearly 48% of the total area and mixed evergreen and deciduous high-low cover density, which is 39.8% of the total area, and agriculture land 8.7% of total area and others base on Arc SWAT. Soil in this river basin is predominantly sandy clay-loam. .

Methods

SWAT is a physically based hydrologic model and requires physically based data (Jacobs and Srinivasan, 2005). Obtaining physically based data for hydrological modeling is often difficult, even in developed countries where data of high quality are generally collected and analyzed (Jacobs and Srinivasan, 2005). The present study concerns the application of a physically based watershed model SWAT2009 in the XeBanghieng watershed to simulate the runoff and Assessment of water resources potential of the XeBanghieng watershed using the SWAT model. The application of the model involved calibration, sensitivity and uncertainty analysis. For this purpose SUFI-2, calibration and validation were used. To get converged solutions 500, 1000, 2000 iterations were needed for each method respectively. A converged solution is reached when the objective functions such as Nash Sutcliffe efficiency reach constant values.

Model Description

SWAT (Soil Water Assessment Tool) is continuous time, spatially distributed model designed to simulate water, sediment, nutrient and pesticide transport at a catchments scale on a daily time step. It uses hydrologic response units (HRUs) that consist of specific land use, soil and slope characteristics. The HRUs are used to describe spatial heterogeneity in terms of land cover, soil type and slope class within a watershed. The model estimates relevant hydrologic components such as evapo-transpiration, surface runoff and peak rate of runoff, groundwater flow and sediment yield for each HRUs unit. The SWAT is imbedded in a GIS interface. Arc-SWAT, Arc GIS extension is a graphical user interface for the SWAT 2009 which is evolved from AVSWAT which is an ArcView extension developed for an earlier version of SWAT. The hydrologic cycle simulated by SWAT is based on the water balance equation1. $SW_t = SW_o + \sum_{i=1}^{t}(R_{day} - Q_{suf} - E_a - W_{seep} - Q_{gw})$….. (1)

Where: SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), E_a is the amount of evapo-transpiration on day i (mm H_2O), W_{seep} is the amount of water entering the vadoes zone from the soil profile on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

To estimate surface runoff two methods are available. These are the SCS curve number procedure (USDA - Soil Conservation Service, 1972 and the Green & Ampt infiltration method. In this study, the SCS curve number method was used to estimate surface runoff. Hargreaves method was used for estimation of potential evapo-transpiration. The equations used in SCS curve number method is as follows;

$$Q = \frac{(R-0.2\,s)}{(R+08s)}, R > 02\,s \quad (2)$$
$$Q = 0.0\,, \quad R \leq 0.2s \quad (3)$$

where, Q is the daily runoff, R is the daily rainfall, and s is the retention parameter. The retention parameter varies in space because of varying soil, land use, management, and slope; and in time because of changes in soil water content. The parameter s is related to CN is as follows:

$$S = 254\left(\frac{100}{CN} - 1\right), \quad (4)$$

CN values for moisture conditions I (CN_1) and III (CN_3) can be estimated using CN_2 as follows:

$$CN_1 = CN_2 - \frac{20\,(100 - CN_2)}{100 - CN_2 + \exp[2.533 - 0.0636\,(100 - CN_2)]} \quad (5)$$

$$CN_3 = CN_2\,exp[0.00673(100 - CN_2)] \quad (6)$$

In which CN2 is the Moisture condition 2 curve numbers for default 5% slope and CN3 is the moisture condition 3 curve numbers for default 5% slope.

Model Inputs

Various input data were collected from different sources. Climatic data i.e. daily precipitation, maximum/minimum air temperature, wind speed, and relative humidity were used as model input. Digital Elevation Model (DEM), land use/land cover, and soil data were also used as model input and are presented in Figures 2 and 3.

Model Setup

The model setup involved five steps:

1) Data preparation;
2) Subbasin discretization;
3) HRU definition;
4) Parameter sensitivity analysis;
5) Calibration and uncertainty analysis.

The required spatial datasets were projected to the same projection called WGS 1984 UTM Zone 48N, which is the transverse Mercator projection parameter for LAO PDR, using software ArcGIS10. The DEM (Digital Elevation Modeling) was used to delineate the watershed and to analyze the drainage patterns of the land surface terrain. DEM mask was used, that was superimposed on the DEM. The Arc SWAT interface uses only the masked area for stream delineation. A predefined digital stream network layer was imported and superimposed onto the DEM to accurately delineate the location of the streams. The Land use/Land cover spatial data were reclassified as per the SWAT model requirement. The SWAT codes were assigned for the different categories of land cover/land use on the map as per the required format. The soil map was linked with the soil database which is a soil database designed to hold data for soils not included in the U.S. The watershed and sub watershed delineation was carried out using DEM data. The watershed delineation process include five major steps, DEM setup, stream definition, outlet and inlet definition, watershed outlet 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 basin. The Arc SWAT interface allows to user to fix the number of sub basins by deciding the initial threshold area (TA). The TA defines the minimum drainage area required to form the origin of a stream. To explore the sensitivity of SWAT 2009 model flow predictions to threshold area values for sub basin delineation scenarios were tested in the XeBangfai river basin using the same DEM. The threshold area for formation of stream line was selected as 5000 hectares. Sub dividing the sub watershed into area having unique land use, soil and slope combinations makes it possible to study the differences in evapo-transpiration and other hydrologic conditions for different land covers, soil, slope, land use, soil and slope database were imported overlaid and linked with the SWAT2009 databases. To define the distributions of HRUs both single and multiple HRU definition options were tested. For multiple HRU definition the Arc SWAT user's manual suggests that a 20% land use, 10% soil and 20% slope threshold are adequate for most applications.

To identify the most reasonable threshold level in the area the suggested threshold and other landuse, soil, slope combinations scenarios were obtain in XeBanghieng watershed. These are 10% landuse, 20% soil and 10% slope. Each scenario was arranged in order of landuse percentage over sub basin area, soil class percentage over landuse area and slope class percentage over soil area. For example, if a 20% soil area is defined in HRU distribution, only soils that occupy more than 20% of a sub watershed area was considered in HRU distributions. Landuses, soils or slope that cover a percentage of the sub basin area less than the threshold level were estimated.

After the elimination processes the area of the landuse, soil or slope is re allocated so that 100 percent of land area, soil or slope in the sub basin is included in the simulation. The parameter sensitivity analysis was done using the Arc SWAT interface for SWAT User's Guide for the whole catchment area. Eight hydrological parameters were tested for sensitivity analysis for the simulation of the stream flow in the study area. In this study, the default lower and upper bound parameter values are used for sensitivity analysis. The details of all hydrological parameters are found in the Arc SWAT interface for SWAT user's manual.

The parameter sensitivity analysis was done using the Arc SWAT interface for the whole catchment area. Twenty hydrological parameters were tested for sensitivity analysis for the simulation of the stream flow in the study area. Here we used the default lower and upper bound parameter values. The details of all hydrological parameters are found in the Arc SWAT interface for SWAT user's manual. The calibration and uncertainty analysis were done using three different algorithms, i.e., Sequential Uncertainty Fitting (SUFI-2) [11], Parameter Solution (ParaSol). This method is chosen for their applicability from simple to complex hydrological models. SUFI-2 algorithms account for several sources of uncertainties such as uncertainty in driving variables (e.g., rainfall), conceptual model, parameters, and measured data. But Para Sol assesses only model parameter uncertainty. The degree to which uncertainties are accounted for is quantified by a P-factor which is the percentage of measured data bracketed by the 95% prediction uncertainty (95 PPU). The 95 PPU is calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through Latin hyper cube sampling [11], which the discharge data recorded during the years 1982-2002 at lower part of the basin as such Kengdon station Figure 4 were used for the model calibration.

Validation is the process of determining the degree to which a model or simulation is an accurate representation of the observed set of data from the perspective of the intended uses of the model. For validation of the SWAT model, the values of simulated discharge at specified locations were compared with the observed discharge during the year 2003-2005. The model performance can be evaluated using established indices like (A) coefficient of determination (R2), (B) Nash-Sutcliffe efficiency ENS. The other factor is the goodness of fit that can be quantified by the coefficient of determination (R2) and Nash- Sutcliff efficiency (NSE) [40] between the observations and the final best simulations. Coefficient of determination (R2) and Nash-Sutcliffe coefficient (NSE) are calculated by equation 7 and 8.

A. Coefficient of Determination

R2 is most often used in linear regression. Given a set of data points, linear Regression gives a formula for the line most closely matching those points. It also gives R-Squared value to say how well the resulting line matches the original data points; R2 ranges from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable (Santhi et al., 2001, Van Liew et al., 2003).

$$R^2 = \left\{ \frac{N(\sum Q_{mod} \cdot Q_{obs}) - (\sum Q_{mod}).(\sum Q_{obs})}{\sqrt{[N(Q^2{}_{mod}) - (\sum Q_{mod})^2].[N(Q^2{}_{obs}) - (\sum Q_{osb})^2]}} \right\}^2 \quad ..(7)$$

Where Q_{mod} is the model simulation value, Q_{obs} the Observation value, N is the total number of data.

B. Nash-Sutcliffe coefficient

$$E_{NS} = 1 - \frac{\sum_{i=1}^{N}[Q_{obs} - Q_{mod}]^2}{\sum_{i=1}^{N}[Q_{obs} - Q_{avg}]^2} \quad (8)$$

Where: E_{NS} is the Nash-Sutcliffe coefficient, Q_{obs} the observed discharge, Q_{mod} the model simulated discharge and Q_{avg} is the average of the observed discharge values. It generally ranges from 0 to 1.Value of E_{NS}greater than 0.65 indicates very good of model prediction, whereas lower E_{NS} indicates poor model prediction, Saleh et al. (2000).

Results and Discussions

In order to assess rainfall-runoff potential of the XeBanghieng river basin which one flow gauge and two ungauge, the Arc SWAT model was calibrated and validated on daily basis for the simulation of surface runoff. Statistical analysis of daily and monthly simulated discharge at Kengdon station during the Calibration period (1982-2002) and Validation period (2003-2005) is presented in tables 1-1, 1-2. The high value of R2 and NSE indicates satisfactory model performance for simulation of runoff during the calibration period (daily and monthly) for the Kengdon station. The comparison of the observed vs simulated discharges (daily and monthly) for the Kengdon station during the calibration period (1982-2002) is presented in Figure 5. From the hydrograph of daily observed and simulated flows at Kengdon (Figure5), it is seen that the simulated flows closely match observed flows except on 18/09/1996 where the peak of simulation was high. According to Eastham et al. (2009), high monsoon rainfall was reported during the month of September 1996. However, the same is not reflected in the observed runoff data. If assumed those data maybe some uncertainty not matches with actual measurement record data for observation at the point Kengdon station.

The scatter plot of the daily and monthly simulated discharge at the Kengdon station during the Calibration 1982-2003 period is presented in Figure 7. Moriasi et al., 2007 presented general performance ratings of the SWAT model for monthly time step simulations. Based on these recommendations, the performance of SWAT model for the study area is very good during calibration period with NSE > 0.65 (Tables.1).

Parameter Sensitivity Analysis:
In this study, the most sensitive parameters for flow predictions were base flow alpha factor (ALPHA_BF) (Arnold et al., 2005), curve number (CN2), available water capacity (SOL_AWC), Manning's 'n' value for main channel (CH_N2), soil evaporation compensation factor (ESCO), groundwater delay time (GW_DELAY),Ground Water "Revap" Coefficient (GW_REVAP), and Threshold depth of water in the shallow aquifer for "revap" to occur (mm) (REVAPMN).

1) Statistical analysis of simulated and observed (Daily and Monthly) discharges for the Kengdon station (2003-2005) is presented in Table 3. The good model performance has been observed during the simulation both of daily and monthly discharges. Comparison of the simulated and observed (Daily and Monthly) discharges at the Kengdonstation (2003-2008) is presented in Figures 8-9. Scatter plots of daily and Monthly Simulated and Observed discharges (2003-2005) at the Kengdon station along the Xebanghieng River from point outlet to Mekong River at point downstream up to Upstream in km 44.96 Ban kengdon Village. Validation period is also presented in Figure 10.
2) It is seen that the model evaluation parameters are very good to satisfactory both for the total and surface flows during entire period of simulation (calibration + validation).

From the daily and monthly hydrographs of estimation simulated flows at the two of un-gauge points (un-guage1 and un-gauge2) during the Calibration and validation period (2003-2005), it is seen that the SWAT model under predicted the high peak values on 18/9/1996 whose value of flow is 11250 m^3/s and also the same day of 18/9/1996 at point of un-gauge 2 is 10550 m^3/s (Figure 10 and 11) in high monsoon reference on information of the local organization (Eastham. J, Mpelasoka. F, Mainuddin. M, 2008). The performance of the SWAT model for the study area is very good during calibration and validation period also with NSE > 0.65 and R2 > 0.70 for both the gauging sites (Table 1 and 3). Therefore, the SWAT model can be adopted for the hydrological evaluation of the river basin in Lao PDR.

Conclusions

The SWAT2009 model was successfully calibrated and validated in the Xebanghieng River Basin using different algorithm. It was applied to the Xebanghieng River Basin for the modeling of the hydrological water balance. The sensitivity analysis of the model to sub basin delineation and HRU definition thresholds showed that the flow is more sensitive to the HRU definition thresholds than sub basin discretization effect. SUFI-2 algorithms gave good results in minimizing the differences between observed and simulated flow in the Xebanghieng River Basin as given below.

1. Value of the coefficient of determination (R2) before calibration and after calibration of the Arc SWAT model was found to be 0.16 and 0.69 for the Kengdon gauging site which daily calibration and the value of Nash-Sutcliff efficiency (NSE) before calibration and after calibration of the SUFI-2 model was found to be 0.19 and 0.67 for the same gauging site.

2. Annual average discharge at the Kengdon gauging site was found to be 516.76 m^3/s. The runoff depth is about 1700 mm, higher than the average annual rainfall at mouth. The monthly discharge is highest in the month of August followed by September and July. Value of the coefficient of determination (R2) of 0.69 (daily simulation) and 0.81 (monthly simulation), Nash-Sutcliff efficiency (NSE) of 0.67 (daily simulation) and 0.79 (monthly simulation), indicates satisfactory calibration of the ArcSWAT model.

3. For the Kengdon gauging site for model validation period (2003-2005) and Annual average discharge is 524.96 m^3/s, Value of coefficient of determination (R2) of 0.85 (daily simulation) and 0.94 (monthly simulation), Nash-Sutcliff efficiency (NSE) of 0.85 (daily simulation) and 0.94 (monthly simulation), indicates satisfactory validation of the Arc SWAT model.

4. Annual average discharge of un-Guage1 study point is 394.99 m^3/s which un-gauge1 area is 389.08 km^2 and un-guage2 study point is 268.23 m^3/s and area of un-gauge2 is 316 km^2.

From the study, by using Arc SWAT the runoff of XeBanghieng river basin can be simulated. This reveal that Arc SWAT can be adopted for the field study of different catchment area of country. For LAO PDR, the SWAT model also produced good simulation results for daily and monthly time steps. The calibrated model can be used for further analysis of the effect of climate and land use change as well as other different management scenarios on strea flow.

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Table 1. *Stream Flow Calibration period (1982-2002) Result for Xebanghieng Rivers at Kengdon stationdaily and monthly Using SUFI-2 methods.*

	Daily Discharge		**Monthly Discharge**	
Parameters	**Observed**	**Simulated**	**Observed**	**Simulated**
Mean	470.89	516.76	514.09	468.59
Standard deviation	828.98	807.57	685.89	673.56
Maximum	7834	11780	4132.05	4110.50
Coefficient of Determination (R2)	0.69		0.81	
Nash-Sutcliffe efficiency (NSE)	0.67		0.79	

Table 2*. The most sensitive parameters for flow predictions of Xebanghieng River*

No.	**parameter**	**Lower Bound**	**Upper Bound**	**Initial Value**	**Calibrated Value**
1	CN2 (%)	-15	15	As per land use	8% decreased for each
2	SOL_AWC	-20	20	0.24	0.53
3	ESCO	0	1	0	0.92
4	GW_REVAP	0.02	0.2	0.02	0.15
5	CH_N2	0.01	0.3	0.014	0.30
6	GW_DELAY	-20	20	31	16.46
7	REVAPMIN	0	200	0	150
8	ALPHA_BF	0.0	1.0	0.05	0.25

Table 3. *Stream Flow Validation period (2003-2005) result for Xebanghieng Rivers at Kengdon station daily and monthly Using SUFI-2, Methods*

	Daily Discharge		Monthly Discharge	
Parameters	Observed	Simulated	Observed	Simulated
Mean	534.16	524.96	532.14	523.00
Standard deviation	937.12	851.98	828.88	728.06
Maximum	5211	5920	3456.94	2786.19
Coefficient of Determination (R2)	0.85		0.94	
Nash-Sutcliffe efficiency (NSE)	0.85		0.94	

Table 4. *Stream flow estimation result after calibration for Xebanghieng Rivers at un-guage1 and un-guage2in daily and monthly period (1982-2005) Using SUFI-2, Methods,*

parameters	Un-guage1	Un-guage2
	m^3/s	m^3/s
mean	394.998	268.2382
Standard deviation	485.98	659.042
maximum	11250	10550

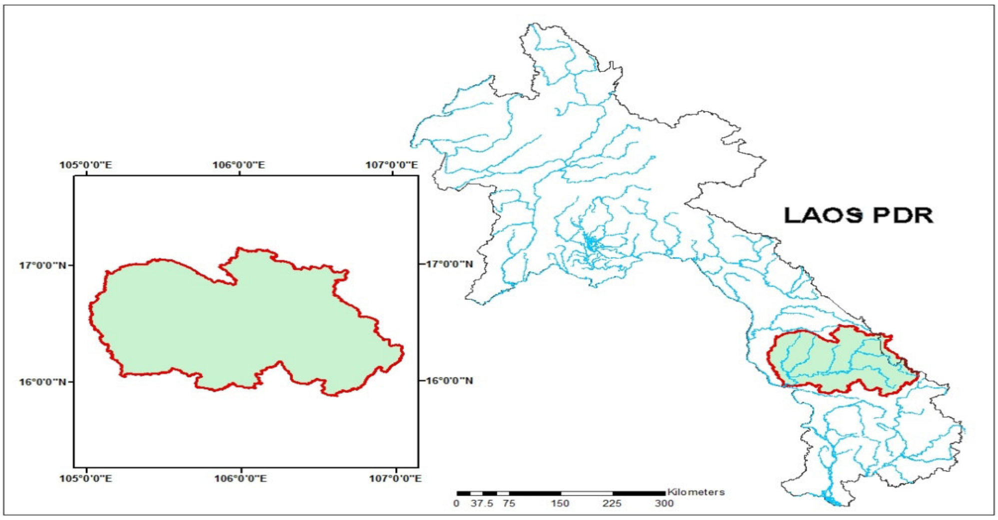

Figure 1. *Location map of study area in Lao PDR*

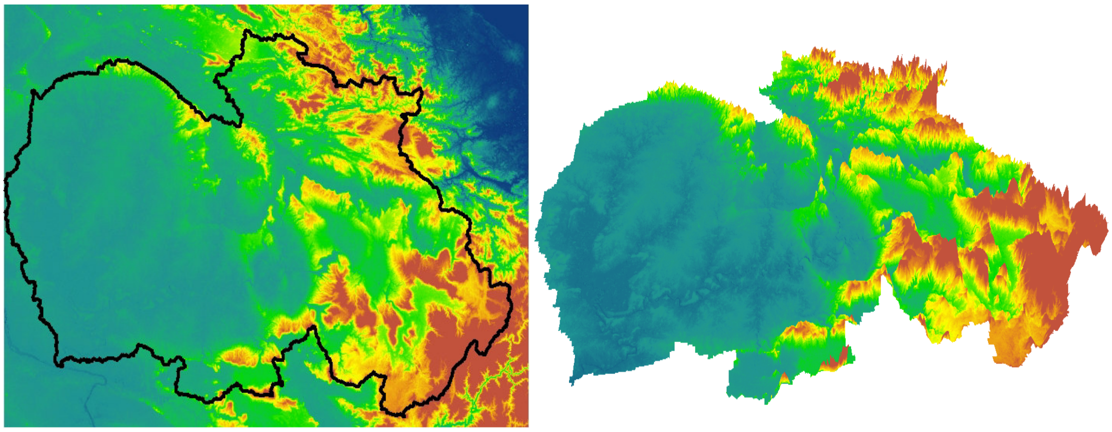

Figure 2. *DEM of the Xebanghieng Basin (meter from mean sea level).*

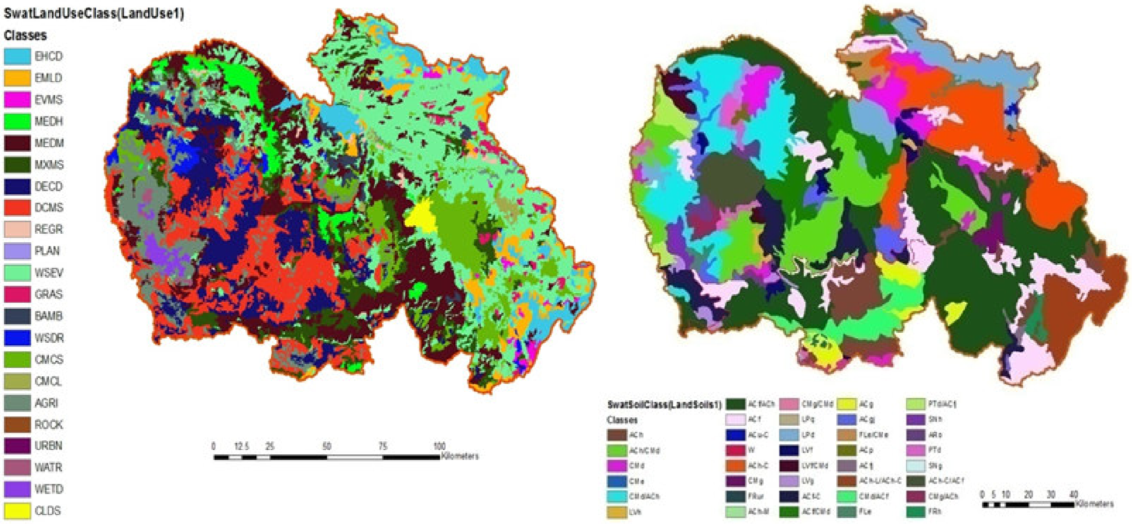

Figure 3. *Land cover and Soil map in Xebanghieng basin*

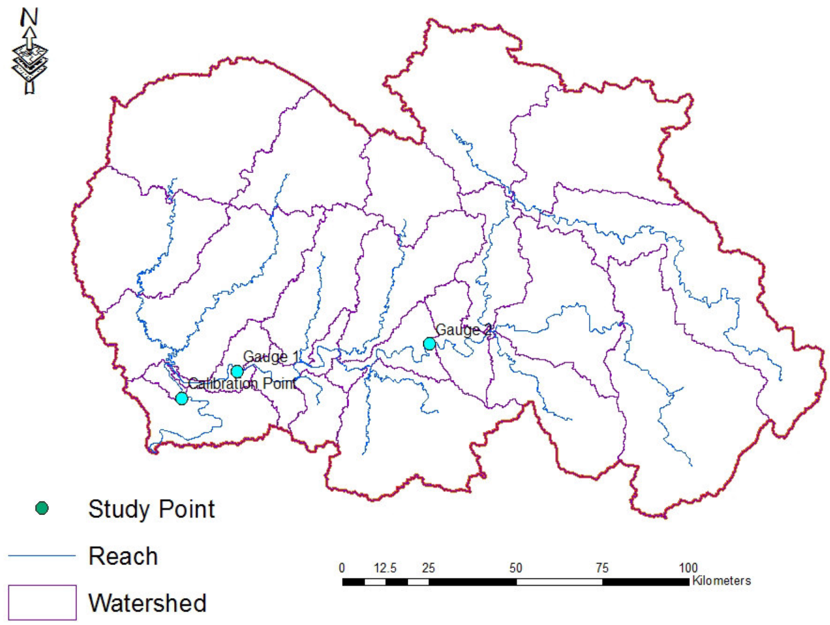

Figure 4. *Calibration point and estimation points*

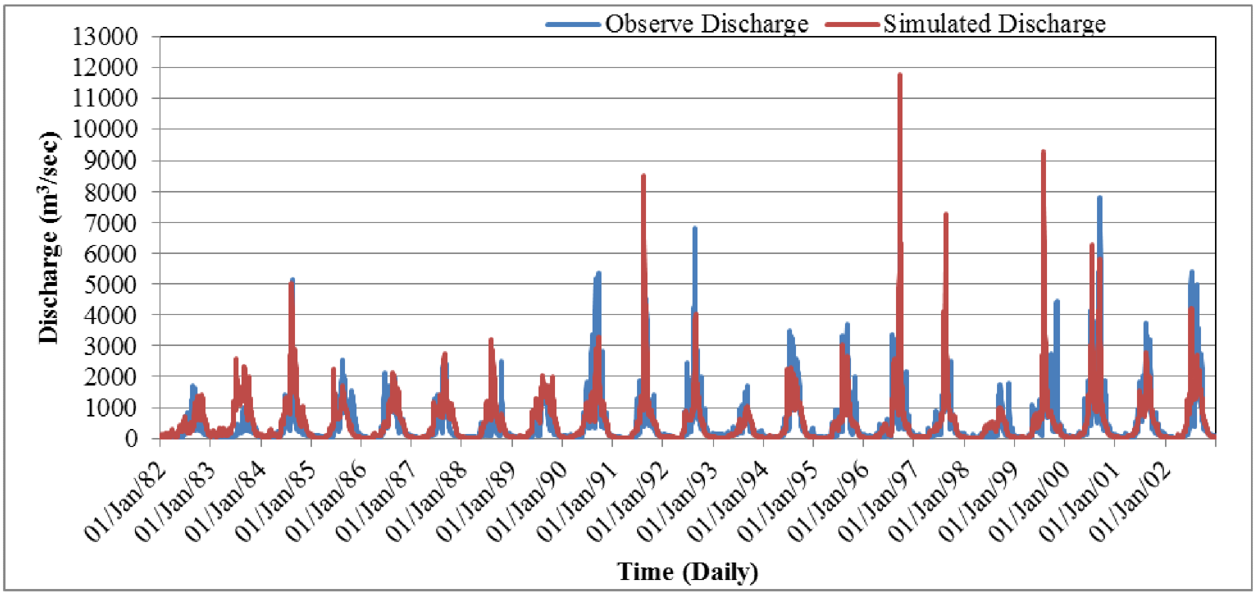

Figure 5. *Hydrograph of Daily Simulated and Observed discharges of the Kengdon station for calibration period (1982-2002).*

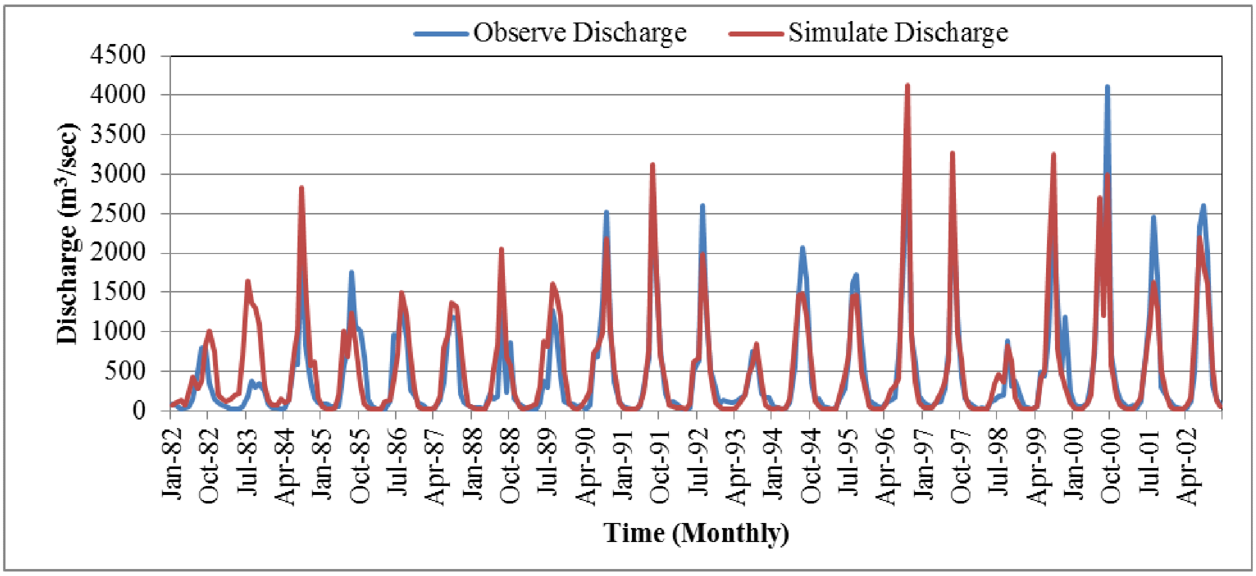

Figure 6. *Hydrograph of Monthly Simulated and Observed discharges of the Kengdon station for calibration period (1982-2002).*

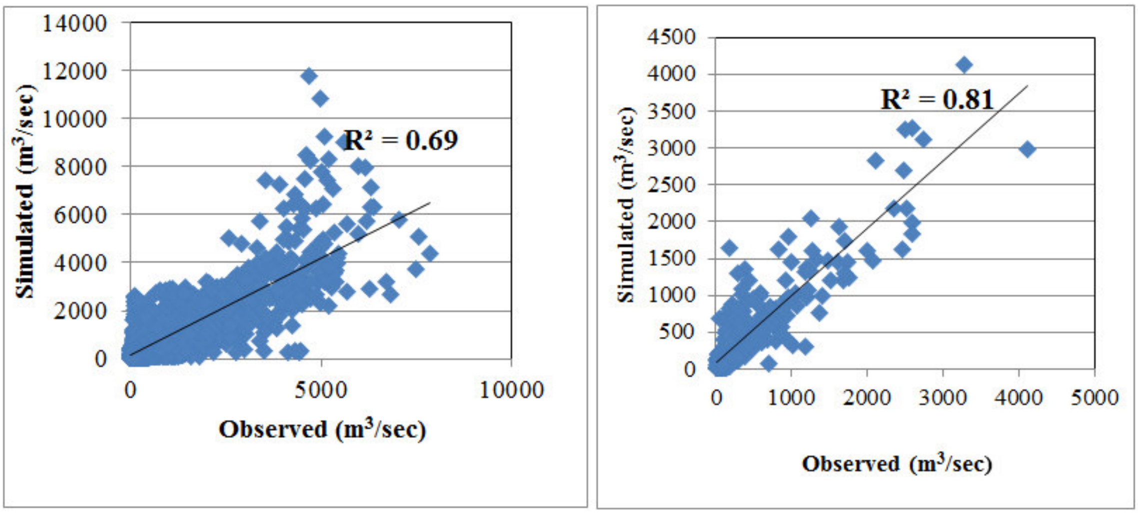

Figure 7. *Scatter plot of Simulated and Observed discharge (daily and monthly) of Kengdon station during the calibration period (1982-2002)*

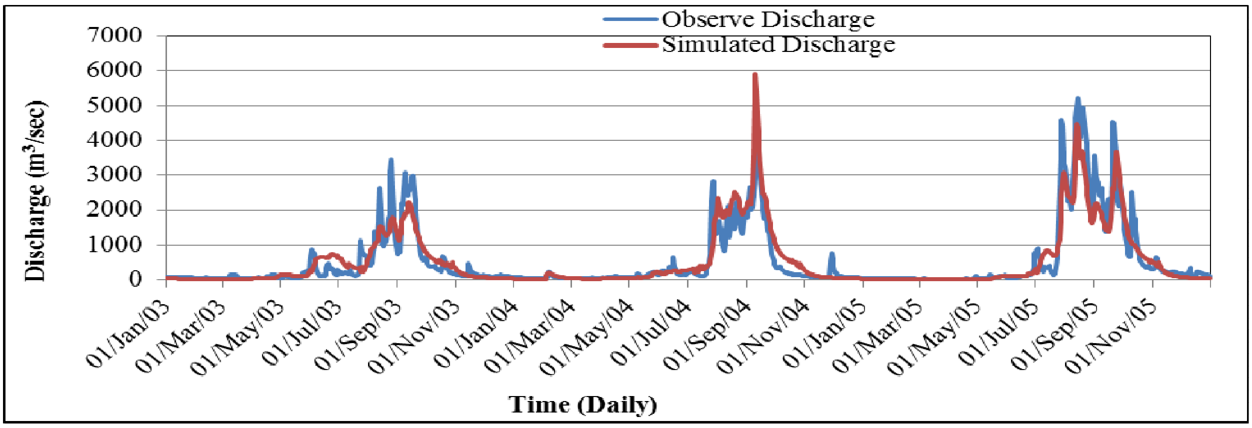

Figure 8. *Hydrograph of daily Simulated and Observed discharges at Kengdon station for Validation period (2003-2005).*

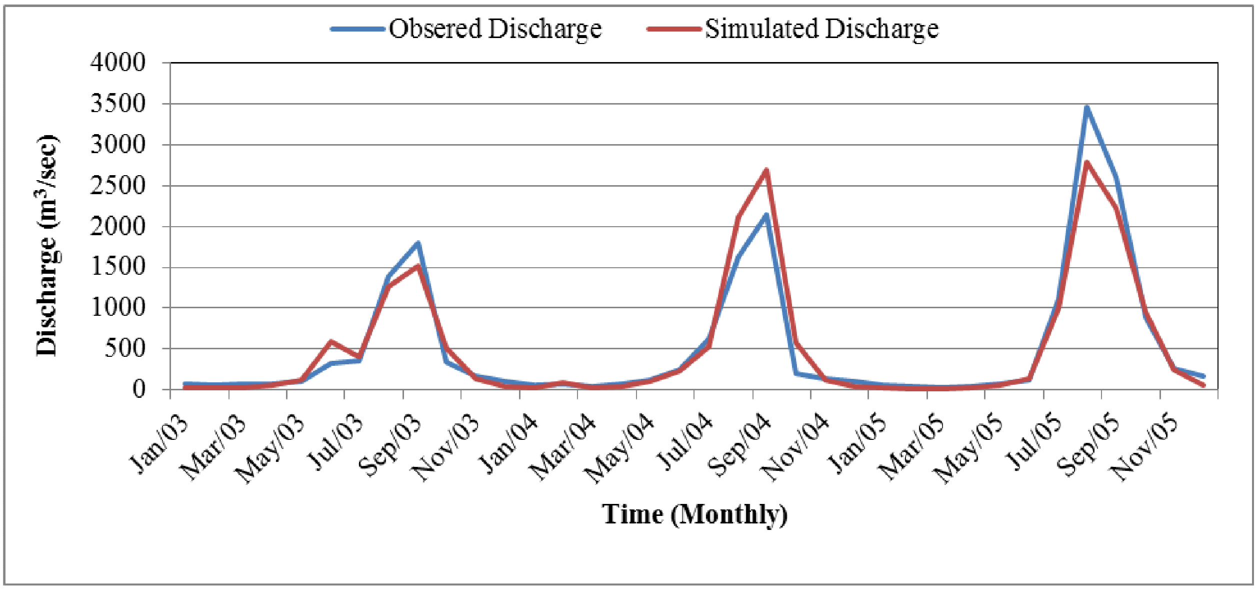

Figure 9. *Hydrograph of monthly Simulated and Observed discharges at Kengdon station for Validation period (2003-2005).*

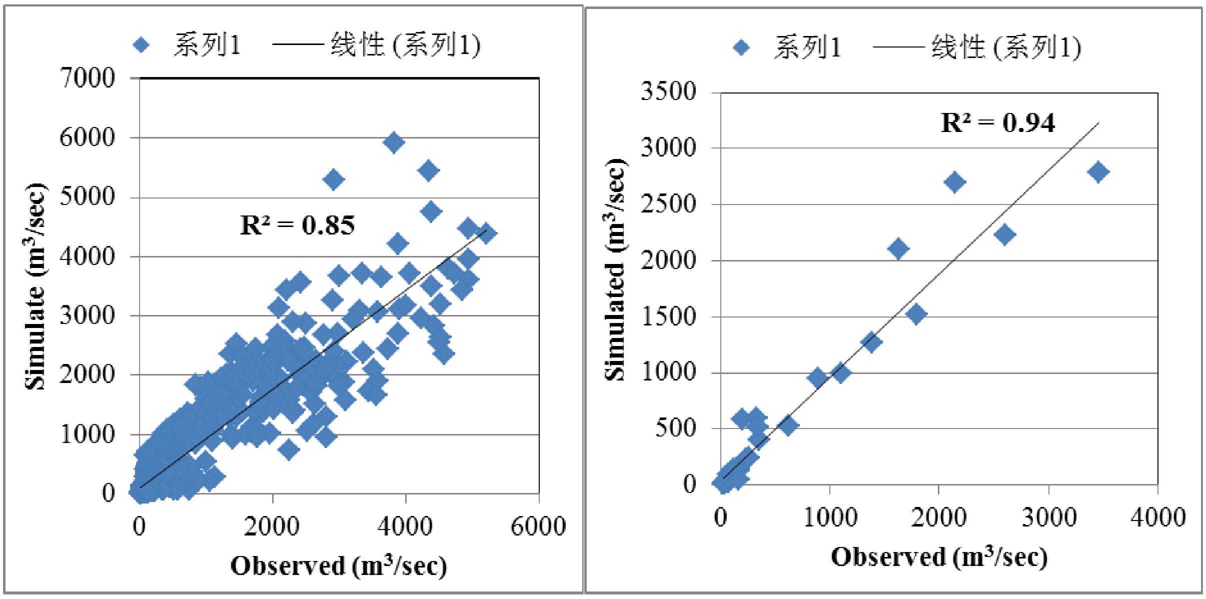

Figure 10. *Scatter plots of Simulated and Observed discharges (daily and monthly) of the Kengdon station during the Validation period (2003-2005)*

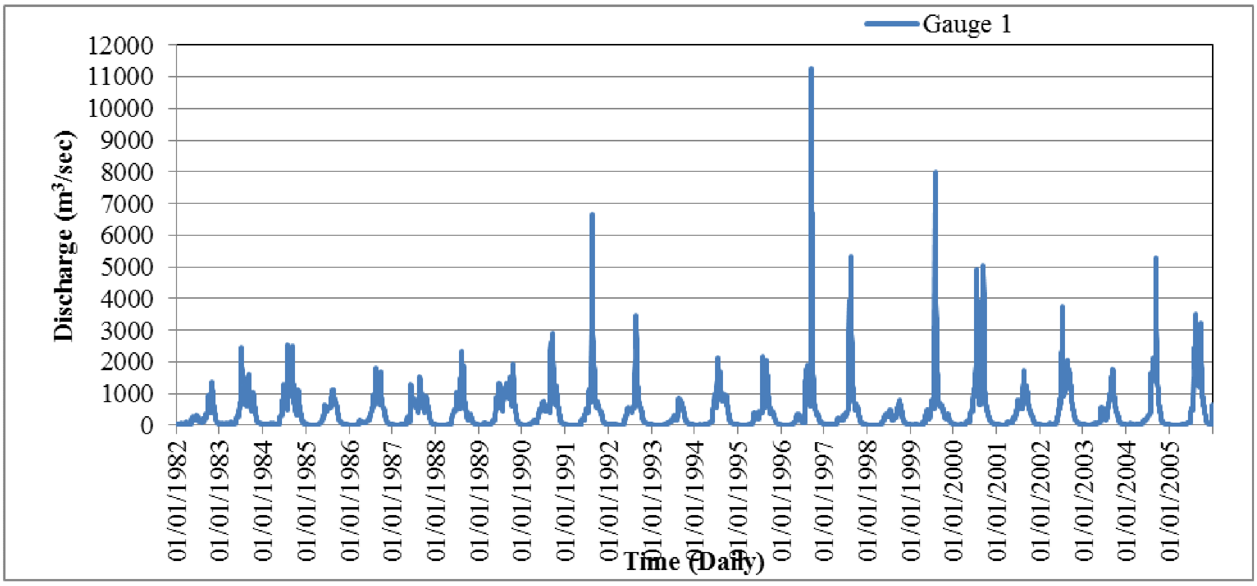

Figure 11. *Statistical analysis of Simulated (Daily and Monthly) discharge at un-gauge1 (1982-2005)*

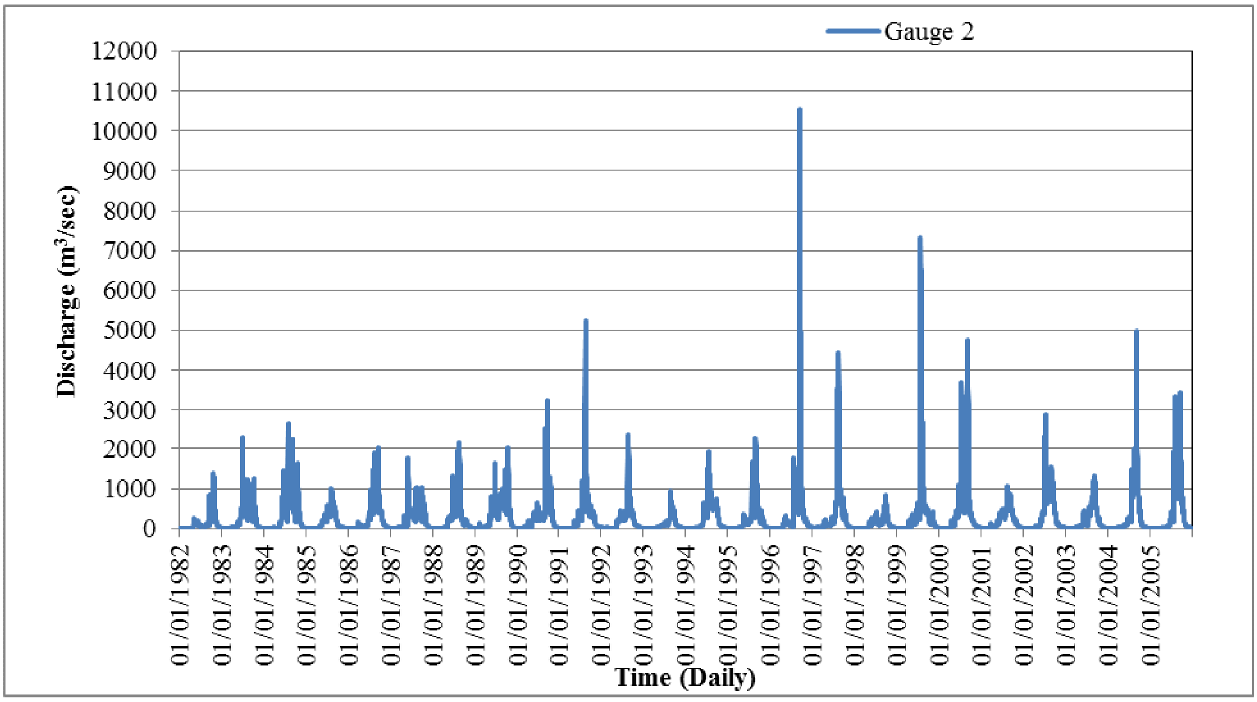

Figure 12. *Statistical analysis of Simulated (Daily and Monthly) discharge at un-gauge2 (1982-2005)*

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