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Validation of SWAT model for stream flow simulation and forecasting in Upper Bernam humid tropical river basin, Malaysia

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Abstract

The study was to evaluate SWAT model for flow simulation and forecasting in the Upper Bernam humid tropical river basin, which is the main source of irrigation water supply for a rice granary. Land use in the study area has rapidly changed from the year of 1984 until today. The study was conducted using 27 years of records (1981–2007). Calibration was performed for the period of 1981 through 2004 while, the period of 2005 through 2007 for the validation of both simulation and forecasting of flow. During calibration, the annual and monthly results were 0.82, 0.65, 0.81 and 0.62 for R^2 and ENS, respectively and 0.99, 0.93, 0.98 and 0.92, respectively during validation. As for forecasting validation, were 0.88, 0.78, 0.86 and 0.74 for R^2 and ENS, respectively. In general model shows good performance in flow simulating as well as forecasting. Five scenarios were performed to identify the individual effect of mixed land use change on stream flow. The scenarios results demonstrate, land use changes are responsible for an increase in the annual flow depth between 8% to 39% while 16% to 59% during high flow months and decreases between 3% to 32% during low flow months. Flow forecasting for the year 2020 using 30 forecasting cycles which found to be the optimal for the study area was performed. The results show decrease by 50% below the monthly irrigation water demand during low flow months, which emphasize the need to include structured best management practices (BMPs) such as ponds to the study area future land development plan to mitigate the future changes in land use on flow quantity. This study showed that SWAT was able to simulate and forecast flow in humid tropical condition successfully and can be used to study the effects of future land use changes on flow.

1 Introduction

Land use changes are expected to have a great impact on watershed hydrology. The resulting higher impervious surfaces cause higher volume of runoff in shorter travel time. Watershed modeling has been used extensively to simulate and analyze the impact of land-use changes on hydrology and stream stability. Lee and Heaney (2003) conducted a hydrologic analysis for an apartment area in Miami using SWMM model to evaluate long-term impacts of urban imperviousness area on runoff volume. The results show that the impervious area, which covers 44% of the catchment, contributes 72% of the total runoff volume during 52 years. On similar aspect, Olivera and DeFee (2007) studied watershed hydrologic response and the relationship between that response and the spatial configuration of the developed areas for the Whiteoak Bayou watershed, Texas over an analysis of 52 years. They concluded that, urbanization is responsible for only 77% and 32% of the increase, respectively, while precipitation changes are responsible for the remaining 39% and 96%, respectively. Many more studies in the literature have attempted to investigate the effect of land use change on watershed hydrology (e.g., Legesse et al., 2003; Pfister et al., 2004; Bari et al., 2005; Bari and Smettem, 2006; Ashagrie et al., 2006; Ward et al., 2008).

The Soil and Water Assessment Tool (SWAT) has been extensively used since 1993 mainly by hydrologists for watershed hydrology related issues (e.g., Srinivasan et al., 1998; Santhi et al., 2001; Cao et al., 2006; Schuol and Abbaspour, 2007; Keshta et al., 2009). It has been widely validated and applied to assess long-term affects of land use changes on stream flow. A comparison between ten hydrological models prediction including SWAT model in Germany, was conducted and discussed by Breuer et al. (2009), Viney et al. (2009) and Huisman et al. (2009). The conclusion was that, SWAT has high calibration efficiencies in the summer than in winter, while performance decreased in the validation period. Fohrer et al. (2001) used SWAT model for the predication of the impact of land use changes on water balance for four meso-scale watersheds in Germany. The results show that the impact of land use change on the annual water balance was relatively small due to compensating effects in a complex catchment. Mishra et al. (2007) used SWAT model to study the impact of land use changes in mixed land-use watershed located in a sub-humid subtropical region in India. The study results showed that the sub watersheds with relatively high forest cover has less runoff and sediment yield whereas the one with more area under cultivation produced higher runoff and sediment. Cao et al. (2008) used SWAT model to simulate two land cover scenarios in the Motueka River catchment, New Zealand, for the purposes of assessing the impacts of land cover change on total water yields, groundwater flow, and quick flow. The results showed that the annual total water yields, quick flow and base flow decreased moderately in the two scenarios when compared with the current actual land use.

Recent SWAT model incorporates both weather generating model and forecasting model, which has enhance the power of the model to generate weather data and forecasting rainfall and temperature for the purpose of runoff forecasting. This has open up a new window for future watershed hydrology studies. In addition, previous studies conducted using SWAT model have proven its ability in satisfying the main requirements for flow forecasting sited by Nash and Sutcliffe (1970) and represent the whole process that occurred in the watershed with sufficiently close output compared to observed. Demirel et al. (2009) compared the prediction accuracy of ANN model with SWAT model. The study results have exposed the ability of SWAT model for flow forecasting with better value of mean squared error than ANN model. In spite of previous studies there exists neither a study nor a methodology for SWAT model validation for flow forecasting in humid tropical region. Hence, in this study, the SWAT model is validated for both flows forecasting and simulating. More over, Optimal forecasted cycles for the watershed is also investigated. This paper provides a methodology for the calibration and validation process of flow for both simulation and forecasting.

2 Study area description

2.1 Location and climate

The Upper Bernam River Basin (UBRB) is located in southeast Perak and northeast Selangor, Malaysia (Fig. 1). The total area of UBRB is 1097 km^2. About 60% of the basin is steep mountainous country rising to a height of 1830 m above the mean sea level in the northern and eastern direction. The basin has a humid tropical climate with relative humidity of about 77%, while the minimum and maximum temperatures are 26 °C and 32 °C, respectively. The annual distribution of rainfall is influenced by two monsoons, the northeast monsoon prevailing from (October to March) and the Southwest monsoon from (May to September). The wet months are October to December and February to May. The dry months are June to August. The average annual rainfall is 1800 mm in the lower part and gradually increases towards the mountainous part of the basin to 3500 mm and the mean annual runoff ranges from 800 mm to 1950 mm. The rainfall-runoff ratio is ranges from 0.35 to 0.61. Annual rainfall-runoff for the study area is shown in Fig. 2.

2.2 Land use and soil types

The land use of the study area were classified into nine classes, viz. forest, oil palm, rubber, urban area, orchard, swamp, grass, water and mining area. Soils were generally classified in to 8 series, viz. steep land, telmakal, serdkdh, mined land, munchser, rengjer, serdbumu, rngbutm. Most of the soils are fair to well drained. Textural classes mostly lie between loam to clay with moderate to average soil moisture holding capacity (Lai et al., 2008).

2.3 Importance of the basin

The study area is the main source of irrigation water supply for the 20 000 ha Tanjong Karang rice granary in Northwest Selangor. In 1936, water for the irrigation scheme was first provided for a single wet-season paddy crop by a weir on the Tengi River via 38 km canal along the southwest border of the existing forest reserve (Zulkifli et al., 2004). In 1957, about 15 km feeder canal was excavated through the peat swamp forest to divert water from the Bernam River to Tengi River, and from there to the main irrigation canal (Fig. 1). This was to augment the water production to cope with water requirement for double cropping. The additional flow from the Bernam River was estimated at between 20 and 25 m^3/s during normal conditions but to drop to 15–20 m^3/s during the critical low flow periods of June–September and December–April. Despite the diversion, the problem of water shortage for the irrigation scheme still exists more or less every alternate year. The recommended peak water demand that should be diverted to the project area at Bernam River Headworks (BRH) is 30.6 m^3/s (JICA, 1987). Many studies have been conducted for various hydrological aspects in the study area (e.g., Amin and Ahmad, 1995; Aimrun et al., 2004; Mustafa et al., 2005; Lai et al. 2008; Rowshon et al., 2009; Alansi et al., 2009; Waleed et al., 2009).

2.4 Land-use changes in the study area

Land-use, topography, rainfall, drainage network patterns are considered the main factors affecting runoff. In the Upper Bernam Basin, land use changes are considered the main factor affecting rainfall-runoff relationship (Alansi et al., 2009). The study area land use has highly changed from the year of 1984 to the present (Fig. 3). The urban area and oil palm have increased while forest and the rest of land use/land covers have decreased. Details of percentages area of the main land-use to total UBRB area are shown in Table 1.

3 Model description

SWAT is a river basin scale model that operates on a daily time-step (Arnold et al., 1998). It was developed at the University of Texas, USA and it is freely distributed on the internet. The academic community has been improving and adjusting the model continually, which allowed it to spread all over the world. SWAT model developed to quantify the influence of land use practices on large, complex watersheds and to predict the effect of management decisions on the water production. Major components of the model include hydrology, weather, erosion, soil temperature, crop growth, nutrients, pesticides, and agricultural management. Weather forecasting is incorporated in SWAT model which allows studying the impact of both predicted weather or/and future land use on watershed hydrology. For that, SWAT was selected for its ability to simulate and forecast stream flow and assess the effect of land use changes on watershed runoff. A comprehensive description of all the components in SWAT can be found in the literature (e.g., Arnold and Allen, 1996; Arnold et al., 1998; Srinivasan et al., 1998; Neitsch et al., 2002; Santhi et al., 2006).

3.1 Input data required

SWAT model needs a lot of data to be defined for the physical watershed representation. This would be data about topography (Digital Elevation Model), climate (daily measured and monthly statistical weather data), and both soil and land use (maps and physical parameters). Data availability as well as quality for a watershed can increase the accuracy of model predication. Precipitation is the key input variable that drives flow and mass transport in hydrological systems. There are 8 rainfall gauging stations and 2 weather stations within the basin having long records to be used in a long-term modeling study. Rainfall and runoff data for the period of 1981–2007 were collected from the Department of Irrigation and Drainage (DID), Kuala Lumpur, weather data for the period of 1981–2007 were collected from the Methodological Department Malaysia (MMD), Kuala Lumpur. Land use maps for the years of 1984, 1990, 1997, 2002 and 2006 were obtained from the Department of Agriculture (DOA), Putrajaya. Land use map for the year of 2020 was obtained from the Department of Town and Country Planning Malaysia (DTCM), Kuala Lumpur. DEM (Digital Elevation Model) of 90 m×90 m was downloaded from the Shuttle Radar Topography Mission (SRTM) located in USGS website (seamless.usgs.gov) which later resampled to 30 m resolution.

3.2 Simulation and forecasting approaches

For the modeling purposes of the Upper Benam River Basin, input data (e.g., DEM, Land use map, soil map, rainfall and weather data) were extracted and generated using the ARCSWAT 2.1.4 model built in ARCGIS 9.2 platform. The first process was watershed delineation which split the basin into 45 subbasins (Fig. 4) according to the terrain and river channels. Further division into multiple hydrological response units (HRUs) comprising of unique land use, soil, and land use management was based on user-defined threshold percentages (Arnold et al., 1998). The next step was the rainfall and weather data files upload. The final stage was writing input files with required input data for the project. General watershed parameters were need to be selected and adjusted according to user knowledge and the historical basin hydrology information such as (PET, rainfall-runoff and channel routing methods) until getting reasonable annual simulated flow compared to observed flow in order to save time during calibration. As for the forecasting process SWAT allows a forecast period to be defined in the simulation period (Neitsch et al., 2002). When the simulation reaches the first day of the forecast period (defined in .cio file) the model replaces the long-term weather generator averages with averages provided for the forecasted period. During the forecast period, the required climatic data (rainfall and temperature) are generated. Number of forecast cycles need to be defined in (.cio) file to obtain higher distribution of weather scenarios (Neitsch et al., 2002).

3.3 Model calibration and validation for simulation

Understanding the model processes, checking the various components such as rainfall to runoff ratio, ET, base flow contribution, etc. are very important to make sure all the major components are represented well for a watershed before attempting either manual or auto-calibration. The model contains both manual and auto-calibration tools.

In this study model parameters were calibrated manually using the observed daily flow. Sensitivity analysis was conducted for the SWAT model to guide calibration process. Seven most sensitive parameters were identified (CN2, SOL_K, SOL_AWC, ESCO, EPCO, ALPHA_BF and C factor) (Table 2). Flow was the first and the only output calibrated for this study. The procedure of model calibration as defined by Santhi et al. (2001), calibration was performed for the annual and monthly flows using observed flows from the flow gauging stations at SKC Bridge (Station No. 3813411 at the outlet of sub-basin 26) for the period from 1981 through 2004. Surface runoff was calibrated and parameters were adjusted many times and compared with observed data. The calibration was stopped when the average measured and simulated surface runoff were within 15% and monthly $R^2>0.6$ and ENS>0.5. The same criteria were applied to base flow after separated from the measured flow using an automated digital filter technique (Nathan and McMahon, 1990; Arnold and Allen, 1999). Calibrated parameters for flow were constrained within the ranges shown in Table 2, while the rest of parameters remain in the range set by the model. In the validation process, the model was operated with input parameters set during the calibration process without any changes for the period from 2005 through 2007.

3.4 Model validation for forecasting

The procedure and periods used for calibrating and validating SWAT model for forecasting purpose were similar to that in simulation purpose; the only difference was the use of average flow results from forecast cycles to be compared with observed values during validation in order to eliminate forecasting error in each cycle. Different forecasting cycles 5, 10, 20, 30, 40 and 50 have been investigated to find the optimal number of forecasting cycles that obtained higher, reliable and closer results compared to observed data. Warm up period was found to be an important factor during model forecasting as well as during simulation.

3.5 Statistical approaches for model performance evaluation

Several statistical approaches were used to check the model performance, viz. coefficient of determination (R^2), Nash-Suttcliffe simulation efficiency (ENS) (Nash and Suttcliffe, 1970), mean absolute error (MAE), root mean square error (RMSE), and Theil's inequality coefficient (U). The R^2 value is an indicator of relationship strength between the observed and simulated values. Nash-Suttcliffe simulation efficiency (ENS) indicates how well the plot of observed versus simulated values fits the 1:1 line. Mean absolute error (MAE), and root mean square error (RMSE), indicates the error between observed and simulated values. Model prediction is considered unacceptable or poor if the R^2 and ENS values are less than or very close to zero while perfect if the values are one. While the MAE, RMSE and U have as the lower limit, the value of zero, which is the optimal value for each of them.

4 Results and discussion

4.1 Evaluation of SWAT model for flow simulation

For calibration process, measured and simulated annual and monthly flows have a good match with slightly under-predicted or over-predicted in some months (Fig. 5). The statistical results for calibration of annual and monthly flows were 0.82, 0.65, 0.81, 0.62, 103.03, 34.03, 82.37, 25.63, 0.0395 and 0.1419 for R^2, ENS, RMSE, MAE and U, respectively (Table 3). As for validation, measured and simulated, annual and monthly flows matched well (Fig. 6). Annual and monthly results were 0.99, 0.93, 0.98, 0.92, 41.45, 17.19, 29.03, 14.85, 0.0139 and 0.065 for R^2, ENS, RMSE, MAE and U, respectively. The results were higher than the recommended minimum values in the literature ($R^2>0.6$ and $\text{ENS}>0.5$) which illustrates that SWAT has represented the whole process that occurred in the watershed with sufficiently close output compared to the observed output. Mean absolute error (MAE), root mean square error (RMSE) and Theil's inequality coefficient (U) of the observed and simulated flows decreased in validation results than calibration. Using the base flow separation filter technique, base flow proportions estimated from the observed flows at SKC Bridge were 66% while, 63% from SWAT simulated flows. The results of surface runoff and base flow for observed and simulated flows revealed a realistic model.

4.2 Evaluation of SWAT model for flow forecasting

In flow forecasting validation, measured and forecasted annual and monthly flows matched well (Fig. 7). The statistical results for validation of annual and monthly results were 0.88, 0.78, 0.86, 0.74, 117.15, 24.96, 88.25, 20, 0.038 and 0.0908 for R^2, ENS, RMSE, MAE and U, respectively. The results were higher than the minimum values in the literature (R^2>0.6 and ENS>0.5) which illustrates the model ability for forecasting (Table 3). Mean absolute error (MAE), root mean square error (RMSE), Theil's inequality coefficient (U) of the observed and forecasted flows were decreased in calibration than forecasting Base flow proportions were 66% and 68% of the observed flows and SWAT forecasted flows, respectively. As for forecasting cycles, 30 cycles appeared to be the optimal cycles number to get a high reliability forecasting for the basin (Table 4). Over all SWAT results for forecasting was of a satisfactory.

4.3 Effect of future land-use changes on flow quantity

Future stream flow quantity is an important issue for paddy fields irrigation in the Upper Bernam River Basin; therefore the effect of land use changes on flow quantity has to be investigated. For this purpose five flow prediction scenarios for the years of 1984, 1990, 1997, 2002 and 2006 using land use of the year 2020 were conducted and compared with actual flows to identify the individual percent of land use changes affected on stream flow with respect to the same amount of rainfall in the study area (Fig. 8). The results reveal, land use changes are responsible for an increase in the annual flow depth between 8% to 39% while, between 16% to 59% during high flow months and decreases between 3% to 32% during low flow months. Since the information of future irrigation water quantity is required for the study area, flow forecasting for the year of 2020 was performed to get an indicator of the possible effect of future land use changes on flow quantity. The results show decreases by 50% below the monthly irrigation water demand during low flow months (Fig. 9).

5 Conclusions

This study presents a methodology for flow simulation and forecasting of SWAT model. The effects of future land use changes on flow quantity were investigated. Additionally, the optimal forecast cycles that appear to have realistic forecasted flow were determined. In general the model has shown good performance in flow simulation as well as forecasting. As for forecasting cycles, 30 cycles were the optimal for the study are. Five flow prediction scenarios for the years of 1984, 1990, 1997, 2002 and 2006 using land use of the year 2020 were conducted to identify the individual percent of land use changes affected on stream flow with respect to the same amount of rainfall in the study area. The scenarios results reveal, land use changes are responsible for increase of annual flow depth between 8% to 39%, while 16% to 59% during high flow months and decreases between 3% to 32%. Finally, flow forecasting for the year of 2020 was performed. The results of forecasted flow show decreases by 50% during low flow months, below the monthly irrigation water demand, which emphasize the need to include structured best management practices (BMPs) such as ponds to the study area future land development plan to mitigate the future changes in land use on flow quantity. The study has proven the effectiveness of SWAT model in simulation and forecasting of the flow in humid tropical condition.

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Table 1. Percentage of main land-use areas to total UBRB area.

Year Land-use	1984	1990	1997	2002	2006	2020 (Planned)
Urban area	0.46	1.57	2.26	3.98	6.46	19.63
Oil palm	8.59	9.04	9.95	13.68	15.93	18.4
Rubber	26.15	25.45	24.61	20.56	17.71	12.82
Forest	56.93	56.37	53.85	51.81	50.08	45.88
Orchard	3.82	2.89	1.83	1.48	1.21	1.06

Table 2. The most sensitive parameters range for model calibration.

Variable name	Model processes	Description	Model range	Change used
CN2	Flow	Curve number	±10%	+10%
SOL_K	Flow	Saturated hydraulic conductivity	0.0 to 2000	Various depend on soil type
SOL_AWC	Flow	Available water capacity of the soil layer	0.0 to 1.00	Various depend on soil type
ESCO	Flow	Soil evaporation compensation factor	0.00 to 1.00	0.30
EPCO	Flow	Plant uptake compensation factor	0.00 to 1.00	0.9
ALPHA_BF	Flow	Base flow alpha factor	0.00 to 1.00	0.0143
C FACTOR	Flow	Cover or management factor	0.0003 to 0.45	Forest: 0.0005 Oil palm and rubber: 0.25 Orchard: 0.20

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Table 3. Annual and monthly SWAT model statistical results for the study area.

Stage	Modeling propose	Period	Time step	R^2	ENS	RMSE	MAE	U
Calibration	Flow	1981–2004	Annual	0.82	0.81	103.03	82.37	0.0395
	simulation	1981–2004	Monthly	0.65	0.62	34.03	25.63	0.1419
Validation	Flow	2005–2007	Annual	0.99	0.98	41.45	29.03	0.0139
	simulation	2005–2007	Monthly	0.93	0.92	17.19	14.85	0.0651
Validation	Flow	2005–2007	Annual	0.88	0.86	117.15	88.25	0.0380
	forecasting	2005–2007	Monthly	0.78	0.74	24.96	20.00	0.0908

Table 4. Annual forecasted flow using different forecast cycles in the study area.

Year	Measured	No. of forecasted cycle					
	(m^3/year)	5	10	20	30	40	50
2005	10 968	8194	9363	9723	10 120	12 054	11 311
2006	24 821	20 384	21 058	20 629	21 192	20 935	20 992
2007	18 783	19 898	19 854	19 389	19 463	19 505	19 544

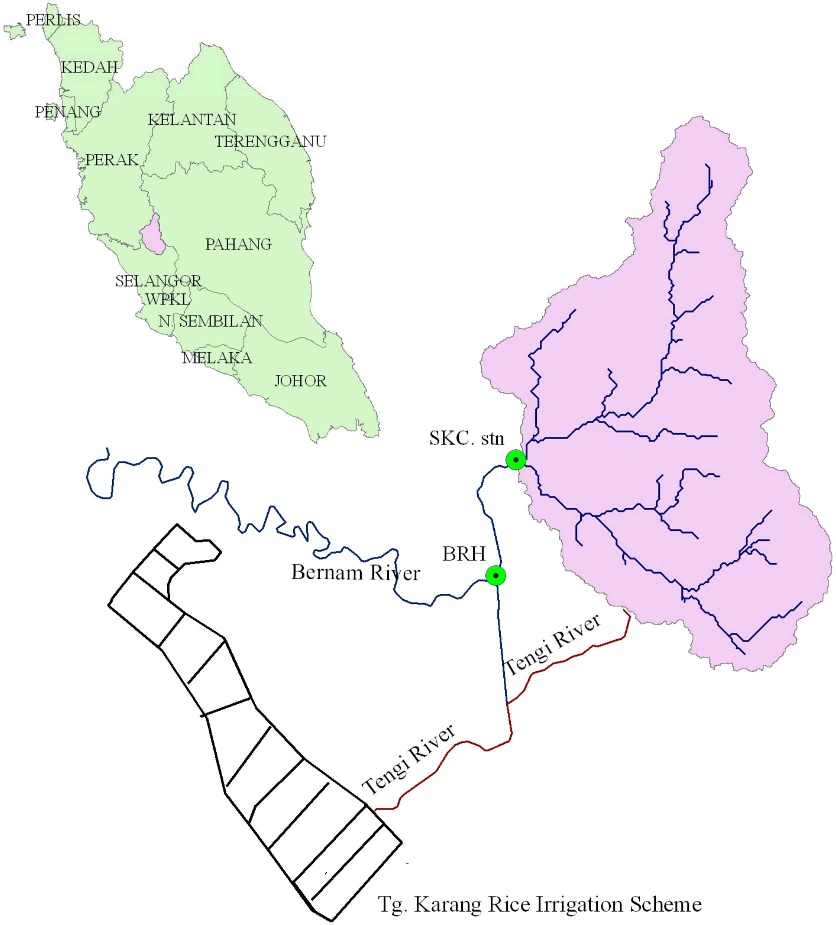

Fig. 1. Locations of the study area and Tanjong Karang rice irrigation scheme.

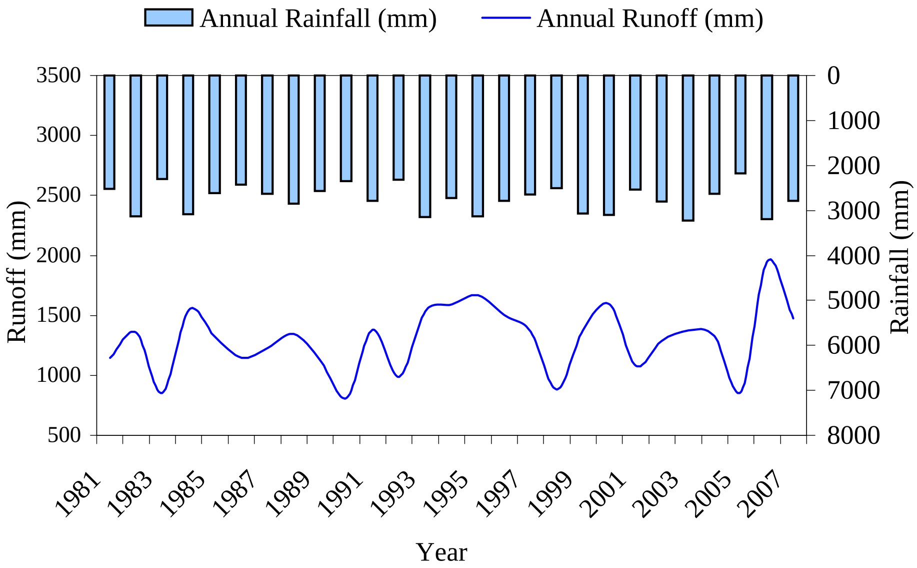

Fig. 2. Annual rainfall-runoff for the study area.

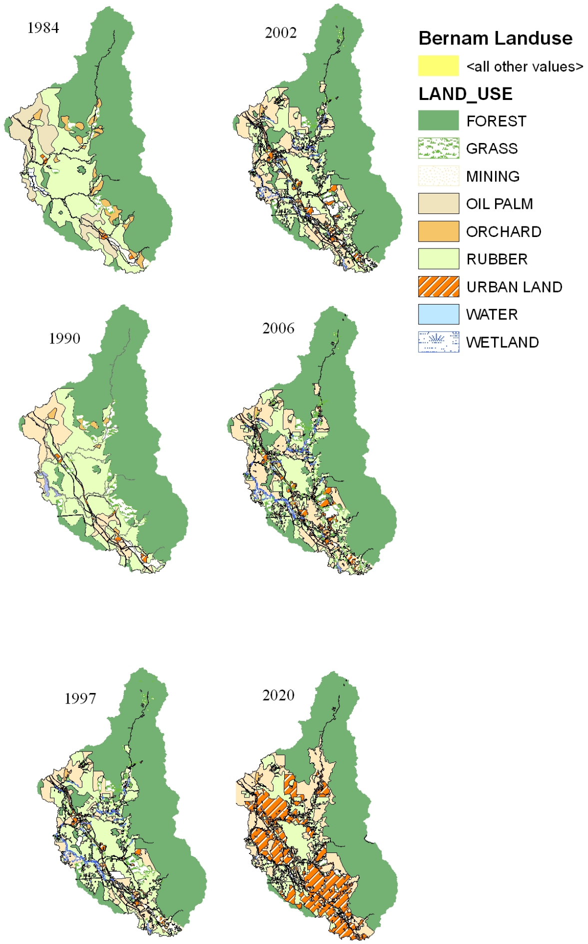

Fig. 3. Land use changes for the study area.

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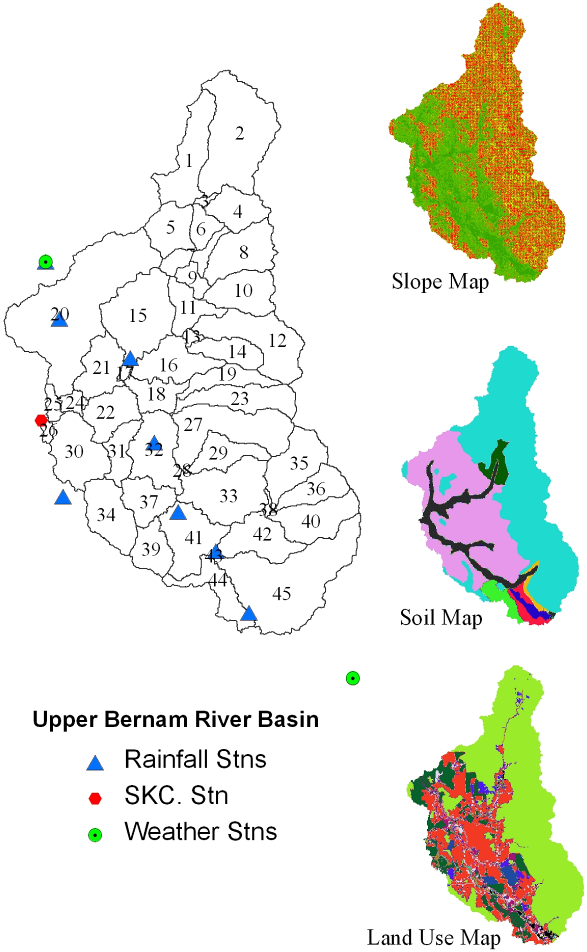

Fig. 4. SWAT model configuration for the study area.

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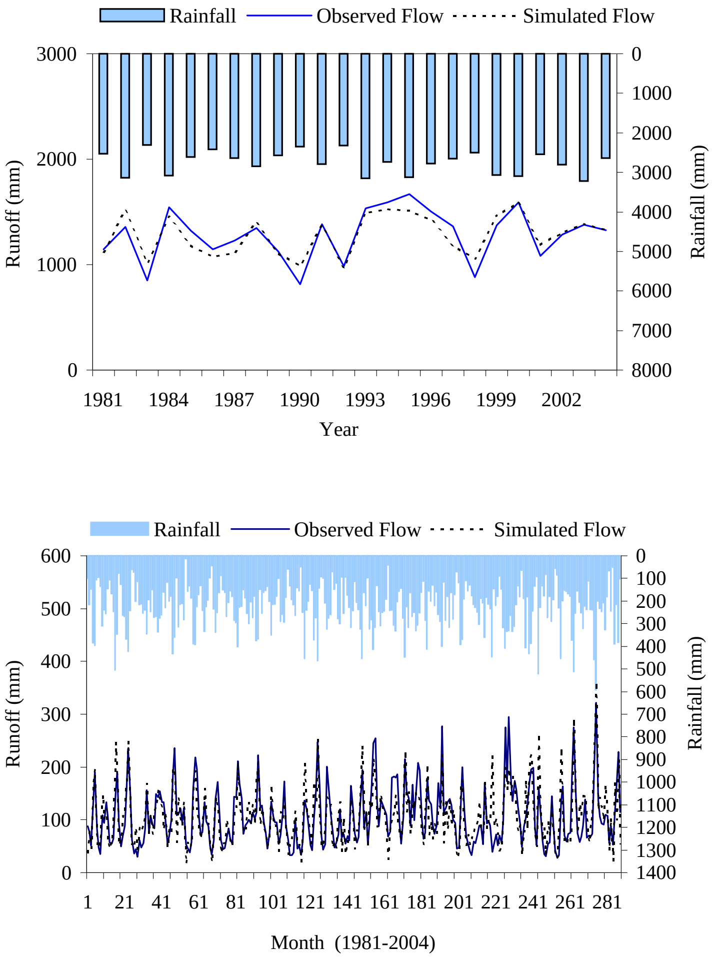

Fig. 5. Observed and simulated flows during calibration period.

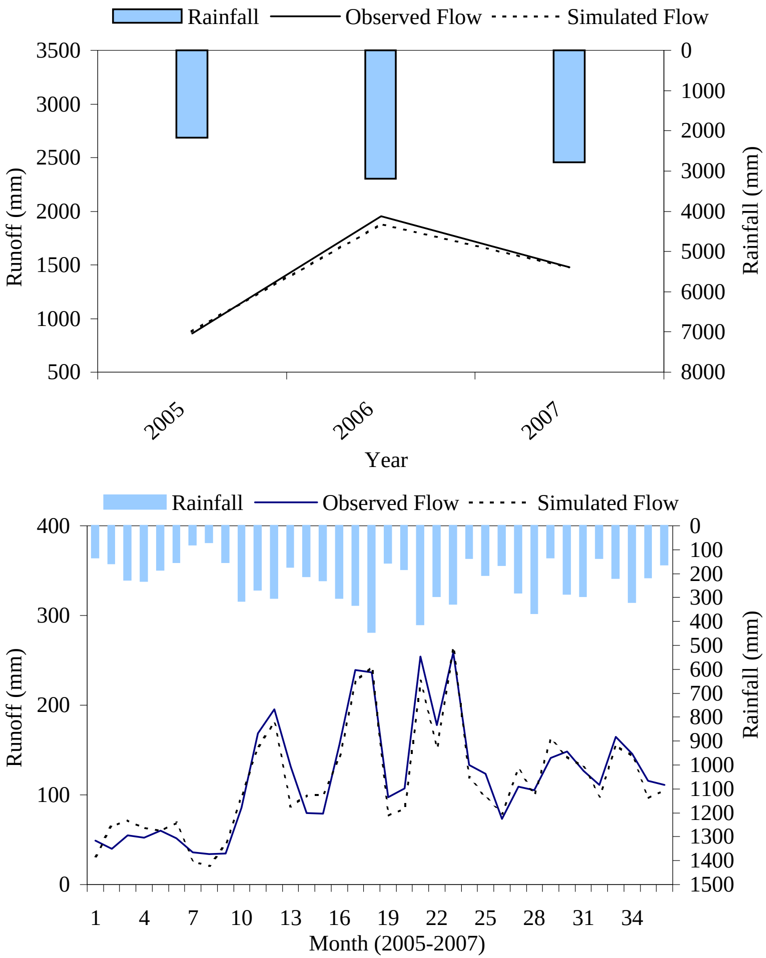

Fig. 6. Observed and simulated flows during validation period.

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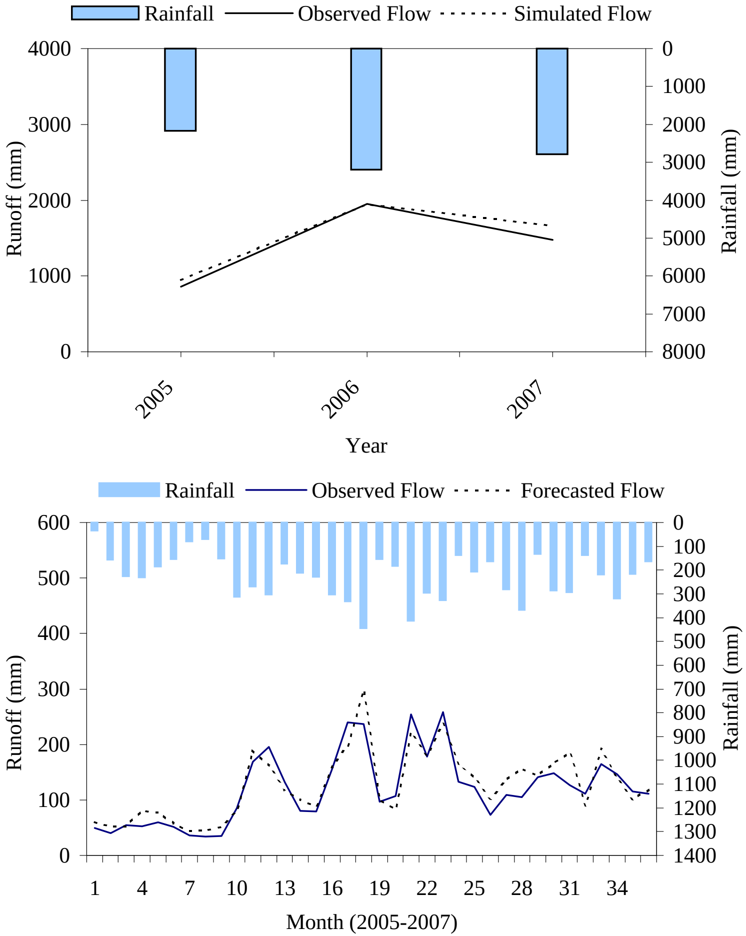

Fig. 7. Observed and forecasted flows during validation period.

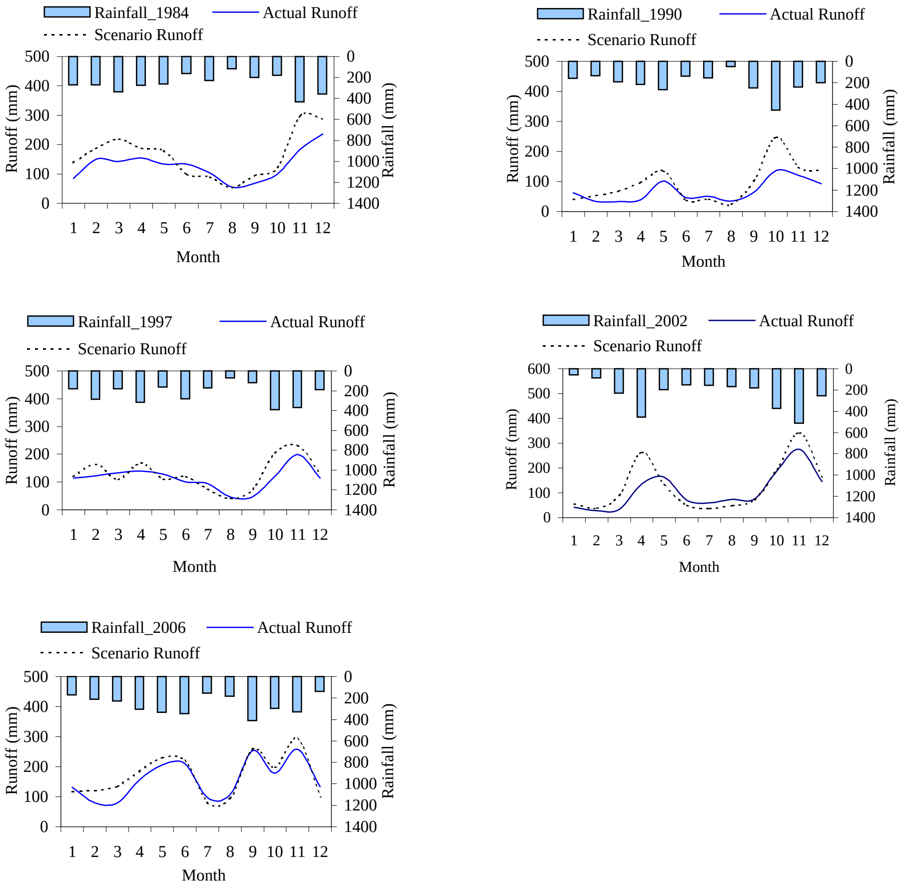

Fig. 8. Flow simulation scenarios for the years 1984, 1990, 1997, 2002 and 2006.

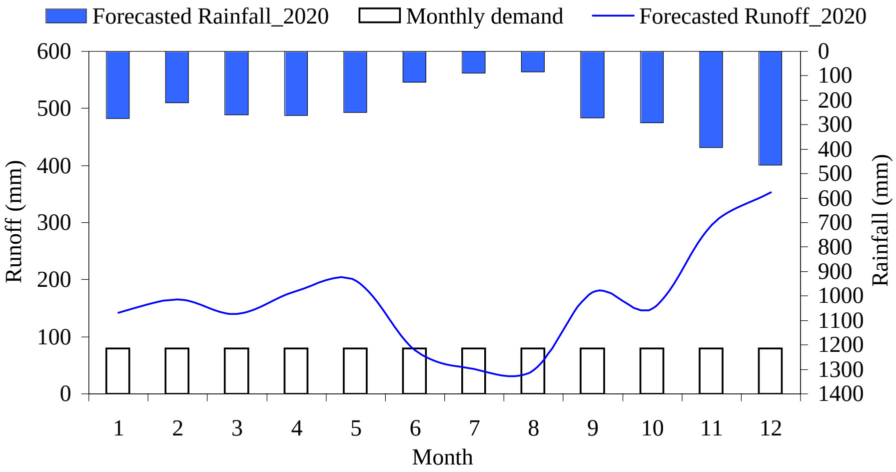

Fig. 9. Forecasted monthly flow for the year of 2020.