A Physically-Distributed Approach to Runoff Modeling In the Hailiutu Watershed, China

Thelma D. Baddoo, Zhijia Li, Danrong Zhang and Guanwen Shao

Abstract**—**Runoff in the semi-arid northwestern China watershed, Hailiutu, from 1957 to 2007 was simulated using the Soil and Water Assessment Tool (SWAT) model. The model was calibrated with and without automated baseflow separation with the Sequential Uncertainty Fitting version 2 (SUFI2) optimization algorithm and objective function as Nash-Sutcliffe efficiency (NSE) in SWAT Calibration and Uncertainty Program (SWATCUP) from 1957 to 1989 with 3 years of warm up period. The calibration results indicate a better performance in the calibration using automated baseflow separation data than calibration without baseflow separation data. In general, the model performance during the calibration process was considered unsatisfactory and therefore could not be validated for the study watershed. Availability of data from hydraulic engineering works could provide some necessary additions to make the model perform better for the Hailiutu watershed.

Keywords**—**Baseflow separation, China, Hailiutu, SWAT

I. Introduction

The Yellow River, the sixth longest in the world and the second prevalent river in China is the most significant freshwater resource for northern and north-western China, providing for about 107 million persons [1]–[3]. Also, the Yellow River has long been deliberated as the 'Mother River of China' because human inhabitants have existed in this region since prehistoric times and therefore the water shortage issue has experienced specific attention all over the world [4], [5]. The middle reaches of the Yellow River basin contribute extensively to the total streamflow and sediment discharge of the Yellow River [6]. According to [7], the Yellow River basin experienced severe drought in the 1980s and 1990s, ensuing in major societal and environmental effects, like drinking and irrigation water shortages and degradation of aquatic ecosystems. For example, in each year of the 1990s, there was no streamflow available for months in the downstream portions of the Yellow River [8]. Simulating hydrological processes in this region therefore is important for water resources management and proper land use policies.

Watershed models are valued tools for predicting streamflow, predominantly where historical observations are accessible for calibration. However, selecting an applicable model configuration for a given application is a challenging task [9]. The Soil and Water Assessment Tool (SWAT) is a deterministic, physically-based distributed river basin model developed to compute the influence of land management practices in watersheds and larger river basins [10] which has been used for varying purposes within different temporal and spatial scales (example see: [11]–[15]). SWAT was developed for use in the simulation of the impact of land management practices and climate on water supplies, sediment, and agricultural chemical yields in large watersheds and larger river basins with variable soils, land-use, and management conditions over long periods of time [16], [17] although it was initially intended to model long-term runoff and nutrient losses from rural watersheds, particularly those dominated by agriculture [10]. It is a continuous time based model which functions on a daily time step at basin scale [18]. The major modules of the model include hydrology, weather, erosion and sediment transport, soil temperature, crop growth, agrichemical transport, and agricultural management [16]. The input data for SWAT necessitates daily precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed data, soils data, land use/management information, and elevation data to drive flows and direct sub-basin routing [19], [20].

SWAT is implanted in a Geographical Information System (GIS) interface. Arc-SWAT ArcGIS extension is a graphical user interface for the SWAT model which progressed from AVSWAT which is an ArcView extension developed for an earlier version of SWAT [21]. This graphical interface makes the use and preparation of inputs into the model more user friendly. The visual interface in ARCGIS allows users to demarcate watersheds from the digital elevation models (DEM), load and categorize HRU's based of spatial land use, slope and soil maps, produce the input files required by SWAT and also conduct sensitivity, calibration and validation of the SWAT model [19].

Due to the fact that the SWAT model is a physically-based, distributed model, it is better capable of representing catchment physical characteristics [22] such as the complex hydrological processes in semi-arid regions. Also, the GIS interface of the model provides user-friendly ways of manipulating and characterizing different catchment processes. Thus the objective of this paper is to simulate runoff in the semi-arid Hailiutu watershed in northwestern China making

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use of the SWAT model to investigate the performance of the complex, data-intensive model.

II. Study Area

The Hailiutu River catchment (38°06’ - 38°50’N, 108°37’ - 109°5’E) lies in the Maowusu semi-desert in the middle segment of the Yellow River Basin in Northwest China with an area of 2645 km^2 [23], [24]. The Hailiutu River, one of the branches of the Wuding River, which is the chief tributary of the middle Yellow River has a catchment surface elevation going from 1020m in the southeast to 1480m above mean sea level in the northwest [24]. The geomorphology of the catchment is made up of undulating sand dunes, low hills at the northern and western water divide, and one prime river valley in the downstream area with a relatively flat area, and the stream network limited to one main river and one branch in the Hailiutu catchment [23]. The catchment is characterized by a temperate semi-arid monsoon climate where the bulk of the precipitation happens in the summer (June to September) while minor amounts of snow fall in winter, with the long-term annual average daily temperature of 8.1 °C, an annual mean precipitation of 340mm/a and long-term average annual pan-water evaporation of 2400 mm/a [23]–[25]. The catchment is primarily covered by thinly to moderately scattered xeric shrub land, which occupies about 88% of the surface area and crop land mixed with wind-breaking trees occupying only 3% of the total surface area [24], [25]. The Hailiutu catchment showing the different meteorological stations and the hydrological station is displayed in Fig. 1.

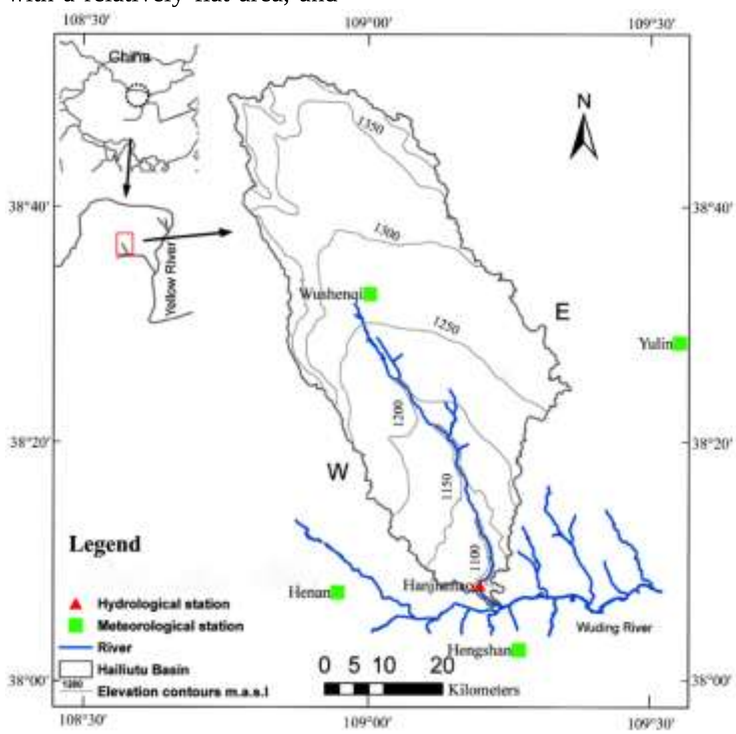

Fig. 1. The Hailiutu watershed showing the meteorological and hydrological stations.

III. Data and Methods

A. Data

The SWAT model requires data such as DEM, precipitation, temperature, wind speed, relative humidity, soil and land use data. A 30m by 30m DEM was acquired from http://www.gscloud.cn/, land use data from http://www.globallandcover.com/ , and 1km by 1km soil data were obtained from the Harmonized World Soil Database. Also, daily gridded climate data (precipitation, temperature, wind speed, relative humidity) were obtained from the "Meteorological Data Sharing Project". These datasets were employed in ArcSWAT, the GIS interface of the model. Furthermore, daily point discharge data from 1957 to 2007 at the Hanjiamao climate station were obtained from the Natural Science Foundation of China (NSFC) "Experimental research on vegetation water source partitioning of riparian zone in arid and semi-arid areas based on multi-tracer technique and its uncertainty" (NSFC51209064) project taking place in the watershed.

B. Methods

The acquired data were studied for variability between rainfall and runoff using daily and annual mean graphs to investigate the rainfall-runoff relationship in the Hailiutu watershed. ArcSWAT2012 was used for SWAT modeling in the Hailiutu watershed. This was done by processing the DEM to demarcate the watershed, using the landuse and soil data to generate hydrologic response units (HRU) and climate data to model runoff and groundwater flow in the watershed. The Baseflow Filter Program, a digital filter-based program, based on a recursive digital filter commonly adopted in signal analysis and processing introduced by [26] is used to separate baseflow from streamflow records for evaluation purposes. This program is made available by the SWAT team at http://swat.tamu.edu/software/baseflow-filter-program/ and fully described in [27], [28].

SWAT Calibration and Uncertainty Program (SWATCUP) was used to calibrate and validate the SWAT model. The model was calibrated for 1957 to 1989 with a warm up period of 3 years and validated for 1990 to 2007. The Sequential Uncertainty Fitting version 2 (SUFI2) optimization algorithm in SWATCUP and objective function as Nash-Sutcliffe efficiency (NSE) was used for calibration. Model performance assessment was done by analyzing the Nash-Sutcliffe efficiency (NSE), the coefficient of determination (R^2), and the percent bias (PBIAS).

IV. Results and Discussion

Exploratory data analysis performed on the data acquired are presented in Fig. 2 and Fig. 3. Fig. 2 illustrates the daily rainfall-runoff relationship in the Hailiutu watershed whereas Fig. 3 displays the mean annual rainfall-runoff relationship in the study watershed. The dashed lines in Fig. 3 show the linear trendline fitted to the annual mean data, the green showing rainfall trend and the black line representing runoff trend with the equation in red displaying the trend equation of the runoff trendline while the blue shows the trend equation of rainfall trendline.

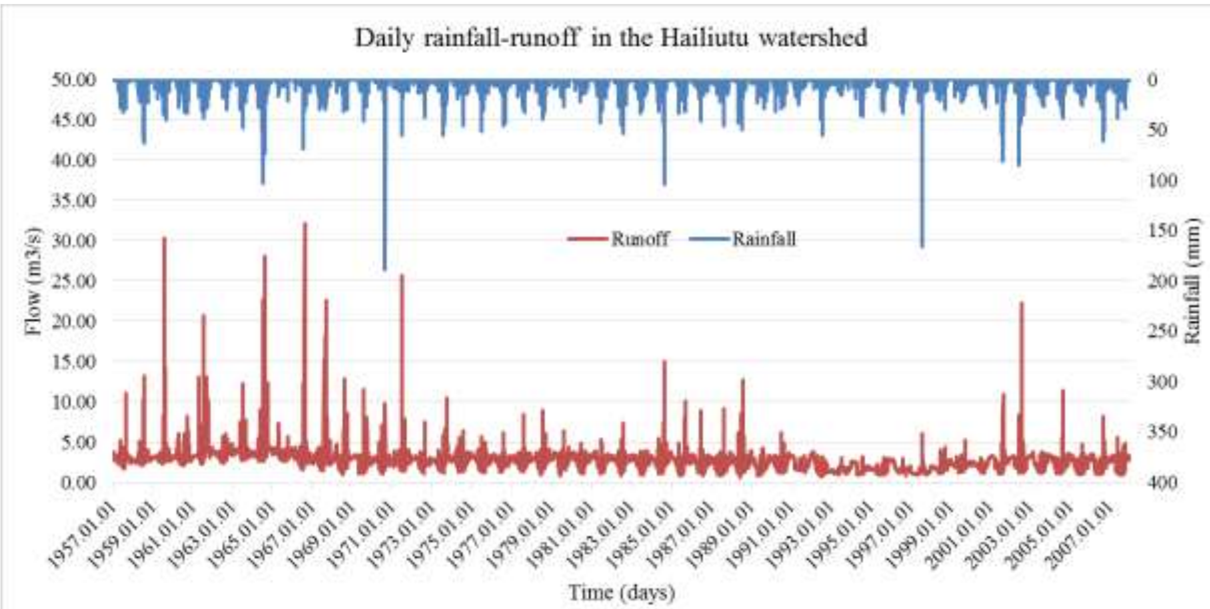

Fig. 2. Daily rainfall-runoff in the Hailiutu watershed.

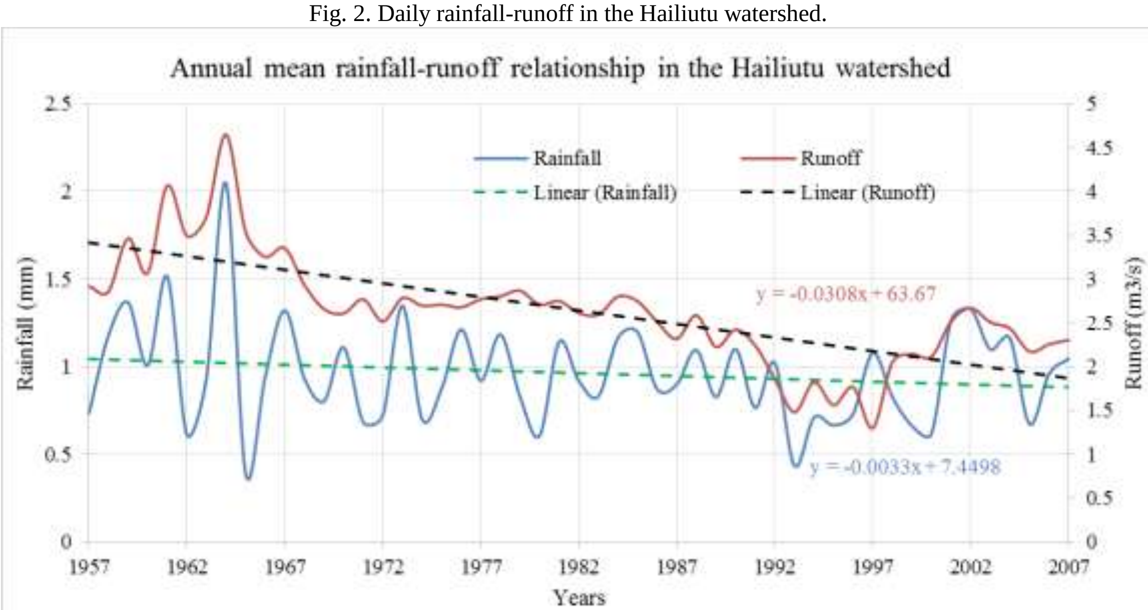

Fig. 3. Annual mean rainfall-runoff relationship in the Hailiutu watershed. The dashed lines show the linear trendline fitted to the annual mean data, the green showing rainfall trend and the black line representing runoff trend with the equation in red displaying the trend equation of the runoff trendline while the blue shows the trend equation of rainfall trendline.

The contribution of subsurface flow to runoff is observed from initial glance of the daily rainfall and runoff in the Hailiutu watershed (Fig. 2) such that when rainfall is zero, runoff is not ever zero. However, from the same figure, it is also observed that high amounts of rainfall does not necessarily produce high flow. This could be due to the continuous development of hydraulic engineering works in the watershed trapping most surface runoff and leaving the discharge at Hanjiamao station to be mostly subsurface flow which [23] confirms by observing that runoff in the Hailiutu watershed consists of 88% subsurface flow. The periods of low rainfall with high flows in Fig. 2 could be as a result of outflow from the various hydraulic engineering works in the study watershed.

The annual mean rainfall and runoff in the Hailiutu watershed (Fig. 3) shows decreasing trends in both data from 1957 to 2007. However, it can be seen that the decreasing trendline of runoff is steeper than that for rainfall. This could be attributed to the impacts of the hydraulic engineering works in the study watershed from 1970 to 1998 within the study period as documented by [25] and [24] such that without available data on the hydraulic engineering works in the Hailiutu watershed for modeling purposes, hydrological models would face challenges in simulating runoff satisfactorily for the study watershed.

C. Calibration results

Calibration results from SWATCUP summary statistics using the Nash-Sutcliffe efficiency as objective function, with and without baseflow separation for the Hailiutu watershed from 1960 to 1989 are presented in Fig. 4 and Fig. 5. Observation of Fig. 4 and Fig. 5 demonstrate that the calibration results were better when the automatic baseflow filter results were used in the calibration process. The figures also show that the best Nash Sutcliffe simulation result in the calibration without the baseflow data (Fig. 4) is 0.29 and the summary Nash Sutcliffe efficiency was also 0.29. However, the best Nash Sutcliffe simulation result for the calibration with baseflow data (Fig. 5) was 0.66 while the summary Nash Sutcliffe efficiency was 0.32, proving that calibration with the data from the automatic baseflow filter program performed better. Also, the coefficient of determination (R^2) for both calibration processes were near equal with the calibration using baseflow data slightly higher. However, the percent bias (PBIAS) for the calibration process without baseflow data was better than that with baseflow data. The simulated and observed hydrographs for the calibration process with baseflow data is presented in Fig. 6.

Goal_type= Nash_Sutcliff No_sims= 800 Best_sim_no= 315 Best_goal = 2.906898e-001

Variable	p-factor	r-factor	R2	NS	bR2	MSE	SSQR	PBIAS	KGE	RSR	MNS	VOL_FR
FLOW_OUT_29	0.34	0.03	0.35	0.29	0.1719	5.5e-001	1.3e-001	0.3	0.56	0.84	0.04	1.00

Fig. 4. Calibration results with no baseflow separation

Goal_type= Nash_Sutcliff No_sims= 800 Best_sim_no= 695 Best_goal = 6.599676e-001

Variable	p-factor	r-factor	R2	NS	bR2	MSE	SSQR	PBIAS	KGE	RSR	MNS	VOL_FR
FLOW_OUT_29	0.35	0.00	0.36	0.32	0.1774	5.3e-001	1.1e-001	1.2	0.56	0.82	0.09	1.01

Fig. 5. Calibration results with automatic baseflow separation

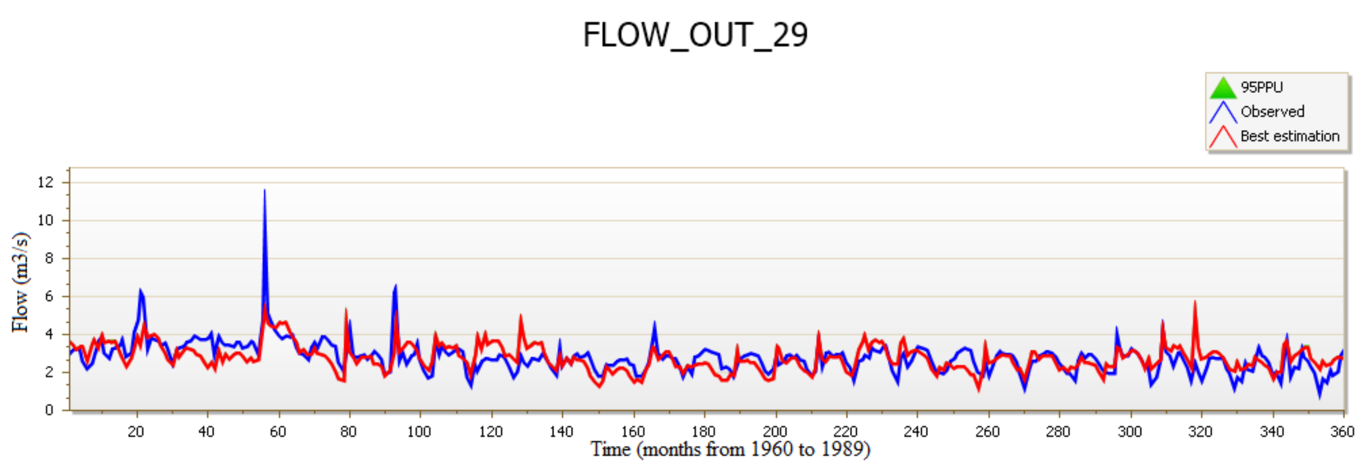

Fig. 6. Hydrograph showing the observed and simulated runoff at the Hailiutu outlet; the blue color representing the observed flow and the red, the simulated.

Fig. 6 shows intermittent underestimation and overestimation of the observed flow with uniformity throughout the calibration period. However, the underestimation of flow on August, 1964 is highly evident.

From Fig. 4, both the best Nash Sutcliffe simulation results and the summary statistics Nash results indicate that the model calibration without baseflow separation for the Hailiutu watershed from 1960 to 1989 was unsatisfactory. However, an observation of Fig. 5 displays the best Nash Sutcliffe simulation results for the calibration period with automatically separated baseflow as a satisfactory model calibration while the Nash Sutcliffe efficiency from summary statistic results indicate unsatisfactory model calibration.

Generally, the model performance was considered unsatisfactory looking at the summary statistic results, albeit the high Nash Sutcliffe result obtained for the best simulation during the calibration process using automated baseflow separation data and therefore the model could not be validated for the Hailiutu watershed.

V. Conclusions

The hydrology and water resource of the Hailiutu watershed was investigated in this study. Exploratory data analysis performed on the raw data demonstrated that the contribution of subsurface flow to runoff in the watershed is highly significant although the watershed is situated in a semi-arid domain. Also, it is observed that high quantities of rainfall does not automatically produce high flows due to the continuous development of hydraulic engineering works which trap most surface runoff and leave the discharge at outlet to be mostly subsurface flow. The Soil and Water Assessment Tool (SWAT) model was used to simulate runoff in the Hailiutu watershed by calibrating with and without automated baseflow separation with the Sequential Uncertainty Fitting version 2 (SUFI2) optimization algorithm and using Nash-Sutcliffe efficiency (NSE) as the objective function in SWAT Calibration and Uncertainty Program (SWATCUP) from 1957 to 1989 with 3 years of warm up period. The calibration results showed that calibrating using separated baseflow data gave the model better performance than calibrating without baseflow data, although the general model performance was considered unsatisfactory. Validation of the model for the Hailiutu watershed from 1990 to 2007 could therefore not be performed in light of the poor calibration results obtained.

Finally, in order to better simulate runoff in the Hailiutu watershed, it is recommended that using seasonal data for modeling be considered to better capture catchment characteristics. Also, data from hydraulic engineering works in the watershed should be made available to provide necessary tools to better model runoff.

Acknowledgments

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