

Hydrological Modeling in A Semi-Arid Region Using HEC-HMS

Meiling Wang¹, Lei Zhang¹, Thelma D Baddoo^{*2}

¹Jiangsu Province Hydrology and Water Resources Investigation Bureau, China

²State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China

¹13913889936@139.com; ¹4409368@qq.com; ^{*}2mzdede2010@gmail.com

Abstract—In this study, the Hydrologic Engineering Centre's Hydrologic Modeling System (HEC-HMS) model was employed to simulate runoff in the semi-arid region of northwestern China, specifically the Hailiutu watershed. The Hydrologic Engineering Centre's Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) was used in conjunction with ArcHydro tools in an ArcMap geographical information system (GIS) environment to create input files of the catchment physical characteristics for the HMS model. The model was calibrated for the time period of 1978-1992. The results showed that the model systematically underestimated winter and spring hydrographs as well as a few summer flows. This was due to the discrepancy between the nonlinear rainfall-runoff response in the watershed and the linear structure of the Soil Moisture Accounting (SMA) model used. Also, the results pointed out that, due to data unavailability on hydraulic engineering in the Hailiutu watershed, the model faced challenges in simulating runoff properly and therefore could not be validated. Ultimately, the model's general performance in simulating runoff in the Hailiutu watershed was found unsatisfactory.

Keywords— China; GIS; Hailiutu; HEC-HMS; Semi-Arid Region; Runoff Simulation

I. INTRODUCTION

Water is necessary for agricultural, domiciliary, industrial, leisurely, and ecological purposes. Its demand already surpasses its supply in many parts of the world, and many more areas are anticipated to face this disparity in the near future [1]. Though the earth is made up of 71% of water, the amount of freshwater available for human use is minute. The awareness that water availability for human use is minimal (despite the earth's composition of mostly water) has increased scientific interest in hydrology and water resources.

Semi-arid areas encompass a great and constantly growing section of the Earth [2], covering some of the fastest-growing population centers worldwide [3]. Since aridity controls the availability of key limited resources, we must further understand semi-arid hydrology and water resource interactions. Though the hydrological cycle is a system that is comparatively easy to grasp and understand, it is harder to enumerate the processes that take place in its system. Hydrological modeling can be used for this purpose [4]. Additionally, hydrological processes in small watersheds are not yet fully understood, but they are accurate precisely for catchments in data-scarce, semi-arid regions [5]. Hydrological modeling has recently become a widespread tool in scientific environments. It is used to understand various processes occurring in the hydrological cycle, including precipitation, evapotranspiration, interception, infiltration, runoff, streamflow (surface flow), groundwater flow to predict changes in water resources, quality and quantity [6, 7].

Studies indicate that the spatial generation of runoff is highly non-uniform and that the factors influencing runoff in arid and semi-arid watersheds are different from those that control the hydrology of wetter settings [8]. The dominant precipitation mechanisms in semi-arid areas result in usually high-intensity, short-interval storms. When accompanied by fairly thin vegetative cover and high evaporation amounts, precipitation mechanisms suggest that the dominant runoff generation mechanism is infiltration of excess overland flow (with saturation-excess runoff typically considered less important) [9]. However, saturation excess runoff may occur in instances such as during the rainy period in valley bottoms [10, 11], or on soils of high infiltration capacity but low storage capacity [12].

Recently, the application of Geographical Information Systems (GIS), remotely-sensed data, and various approaches to the development of hydrological models [13-15] has led to models which are able to more accurately represent different catchment processes [16]. For hydrological modeling efforts, GIS, especially through their capacity to process digital elevation models (DEMs), have afforded modelers with new platforms for data management and visualization [17, 18]. Further improvement was achieved by incorporating catchment models into GIS, which streamlines data input and provides enhanced interpretation of model outputs [19].

This paper's main objective is to evaluate the use of the semi-distributed HEC-HMS model, in order to investigate the rainfall-runoff interactions in the semi-arid Hailiutu watershed of northwestern China. Our method was to prepare inputs using remote sensing and GIS techniques.

A. Study Area

The Hailiutu River catchment ($38^{\circ}06' - 38^{\circ}50'N$, $108^{\circ}37' - 109^{\circ}5'E$) lies in the Maowusu semi-desert in the middle section of the Yellow River Basin in Northwest China, with an area of 2645 km^2 [20, 21]. The Hailiutu River is one of the divisions of the Wuding River, which is the key tributary of the middle Yellow River and has a catchment surface elevation ranging from 1020m in the southeast to 1480m above mean sea level in the northwest [21]. The catchment's geomorphology is made up of undulant sand dunes, stumpy hills at the northerly and western water boundary, and one principal river valley in the downstream, moderately flat area. The stream network is limited to one main river and one branch in the Hailiutu catchment [20]. The watershed is characterized by a temperate, semi-arid, monsoon climate where the majority of the precipitation takes place in the summer (June to September). In winter, there are small amounts of snow. The long-term yearly mean daily temperature from 1961 to 2006 is 8.1°C . The catchment features an annual mean precipitation of 340mm/a and a long-term mean yearly pan-water evaporation of 2400 mm/a [20-22]. The catchment is mainly covered by sparsely to moderately distributed xeric shrub land, which engulfs around 88% of the surface area and crop land mixed with wind-breaking trees occupying only 3% of the total surface region [21, 22]. Fig. 1 shows the Hailiutu catchment with nearby meteorological and hydrological stations.

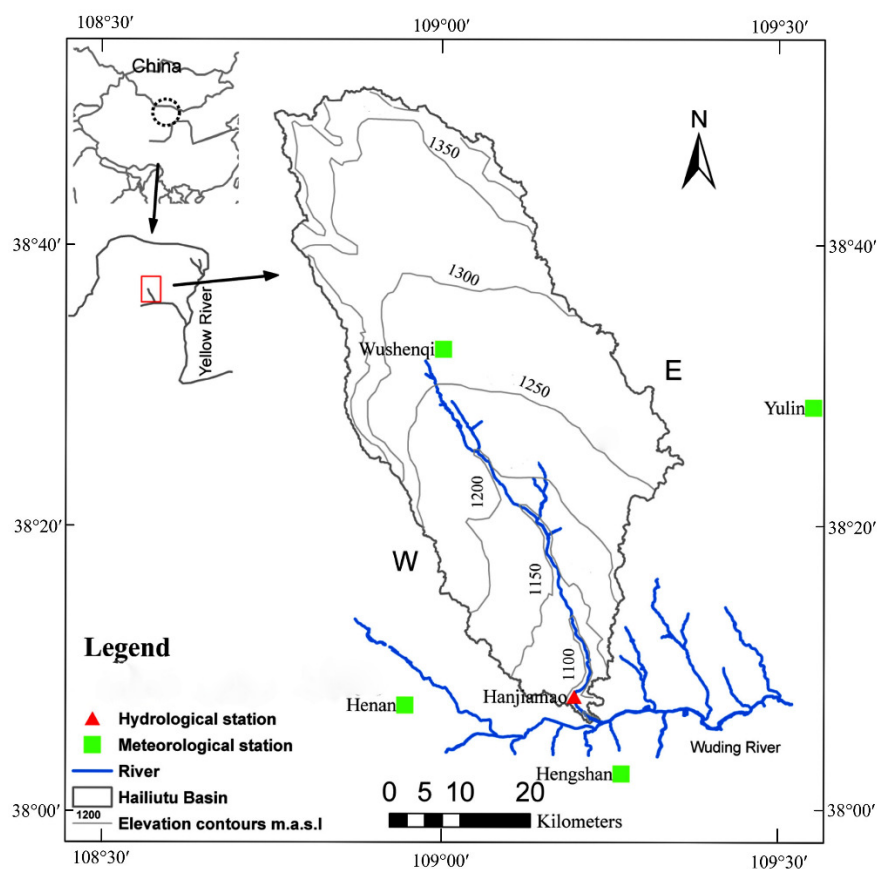


Fig. 1 Map of the Hailiutu watershed showing the meteorological and hydrological stations from which data was obtained

B. Justification for using HEC-HMS

The Hydrologic Engineering Centre's Hydrologic Modeling System (HEC-HMS) was designed by the United States Army Corps of Engineers (USACE) as an updated version of the USACE HEC-1 precipitation-runoff model [23].

The software models rainfall-runoff and channeling processes of catchment systems. It models both natural and controlled in values in a widespread variety of geographical regions, such as large river basins and small municipal and natural watersheds [23, 24]. It is a deterministic, semi-distributed, event-based/continuous, mathematically based (conceptual) model that adopts other distinct models to characterize each element of the runoff process (evaporation, surface runoff, infiltration, and groundwater recharge). Therefore, this one model contains within itself models that calculate runoff volume, models of direct runoff, models of base flow, and models of channel flow [23-25]. This model takes into account the spatial distribution of basin features by partitioning a basin into sub-basins that are considered homogenous in land use, soil type, and other catchment features. Furthermore, spatial data sets can be organized in GIS platforms using HEC-GeoHMS and then directly imported into HEC-HMS [25].

The model we discuss employs a graphical user interface to construct a watershed model and to set up the precipitation and control variables for modeling [26]. Therefore, it provides a user-friendly interface and is relatively easy to use [27]. The interface is based on the conception of direct management and allows the user to quickly ascertain, view, and adjust all of the data entities used in the program [28]. Each model run incorporates a basin model (describing catchment connectivity and physical characteristics), meteorological model (storing the precipitation and evapotranspiration data crucial to model watershed processes), and control specifications (defining the simulation time interval) with run options to attain outcomes [24]. Details of model structures of HEC-HMS can be found in [23] and [28].

HEC-HMS has been used successfully in a number of studies worldwide, including flood forecasting/rainfall-runoff modeling [24, 29, 30], reservoir management [26], water resources assessment [31], land use change impacts [25], and many others.

II. MATERIALS AND METHODS

A. Data

We obtained daily mean areal rainfall data and point runoff data (for 1978-2007) collected at the Hanjiamao Hydrological Station from the Natural Science Foundation of China (NSFC). ("Experimental research on vegetation water source partitioning of riparian zone in arid and semi-arid areas base on multi-tracer technique and its uncertainty" (NSFC51209064) took place in the watershed.) The annual mean evapotranspiration (ET) was transformed into average monthly ET for the purposes of this study.

Also, spatial data in the form of a digital elevation model (DEM) was downloaded from the land cover website at: <http://glcfapp.glc.umd.edu/>. A filled finished-B 90m by 90m resolution SRTM (Shuttle Radar Topography Mission) DEM was downloaded from the website on May 18, 2016. We adopted the DEM to define the Hailutu watershed and to examine the drainage configurations of the land surface topography.

B. Methodology

We studied the acquired data for variability between rainfall and runoff using daily mean monthly and annual graphs to investigate the rainfall-runoff relationship in the watershed. Before hydrological modeling, our methodology can be separated into four main stages: (1) attaining the geographic locations of the study's watershed; (2) DEM processing, defining streams and watershed characteristics, terrain processing, and basin processing; (3) importing the processed data to HEC-HMS; and (4) integrating the observed data with the processed DEM for model simulations as adopted by [30].

We employed the Geospatial Hydrologic Modeling Extension (HEC-GeoHMS), alongside the ArcHydro extension in ArcMap 10.0, to demarcate the physical characteristics from the SRTM data, and also to produce a stream network and sub-basins and their boundaries. We also generated the input file in the form of the basin model for use in HEC-HMS. HEC-GeoHMS is a free domain extension to ESRI's ArcGIS software and the Spatial Analyst extension; it aids in envisioning spatial information, recording watershed characteristics, accomplishing spatial analysis, demarcating sub-basins and streams, and creating inputs for the hydrologic model that can simply and proficiently generate hydrologic inputs to be used directly with the Hydrologic Engineering Center's Hydrologic Modeling System, HEC-HMS software [32]. For this study, we used the HEC-GeoHMS, version 5.0.

In our analysis, the HEC-HMS (version 4.1) was employed for runoff simulation. The basin model signifies the physical watershed. As described earlier, the basin model was prepared in HEC-GeoHMS and imported into the HEC-HMS.

The meteorological model performs meteorological data analysis of factors such as precipitation, evapotranspiration, and snowmelt [28]. The meteorological model makes use of both point and gridded precipitation data. In this study, 30-year daily point precipitation data was used. Also, a monthly averaged evapotranspiration was added to the meteorological model of the HEC-HMS model.

For calibration purposes, we entered time-series data of the point precipitation and 30-year daily observed discharge data at the outlet of the watershed into the model.

The soil moisture accounting module (SMA) was selected as the precipitation loss model, the Clark method as the transform model, the linear reservoir module as the base flow model, and the Muskingum module as the channel routing model.

To account at least partially for the Hortonian infiltration-excess mechanism of runoff production in semi-arid regions, the time interval used in the control specification was 6 hours.

We calibrated the model using 15-year data from 1978 to 1992. The remaining 15 years (1993-2007) were used for validation. The model was calibrated both manually and automatically using the univariate gradient search method and the Nelder Mead algorithms provided in the HEC program. The Nash-Sutcliffe efficiency was used as the objective function.

The model's performance was assessed using statistical measures as the root mean square error (RMSE), mean absolute error (MAE), percent error in peak flow (PEPF), percent error in volume (PEV), and the Nash-Sutcliffe Efficiency criteria (E), which are expressed as [23, 28, 33,34, 35]:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (O_i - P_i)^2} \quad (1)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n (O_i - P_i) \quad (2)$$

$$PEPF = 100 \left| \frac{P_{peak} - O_{peak}}{O_{peak}} \right| \quad (3)$$

$$PEV = 100 \left| \frac{V_O - V_P}{V_O} \right| \quad (4)$$

$$E = 1 - \left(\frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \right) \quad (5)$$

Where O = observed values; P = predicted values; n = number of cases; P_{peak} = predicted peak flow; O_{peak} = observed peak flow; and V_O (V_P)= volume of the observed (predicted) hydrograph.

III. RESULTS AND DISCUSSION

The exploratory data analysis we executed on the data acquired is presented in Figs. 2, 3 and 4. Fig. 2 illustrates the daily rainfall-runoff relationship in the Hailiutu watershed, while Fig. 3 and Fig. 4 represent the mean monthly and annual rainfall-runoff relationship in the study's watershed. The dashed lines in Fig. 4 show the linear trendline fitted to the annual mean data; the green line shows rainfall trend; and the black line represents flow trend. The equation in red displays the trend equation of the flow trendline, while the blue shows the trend equation of the rainfall trendline.

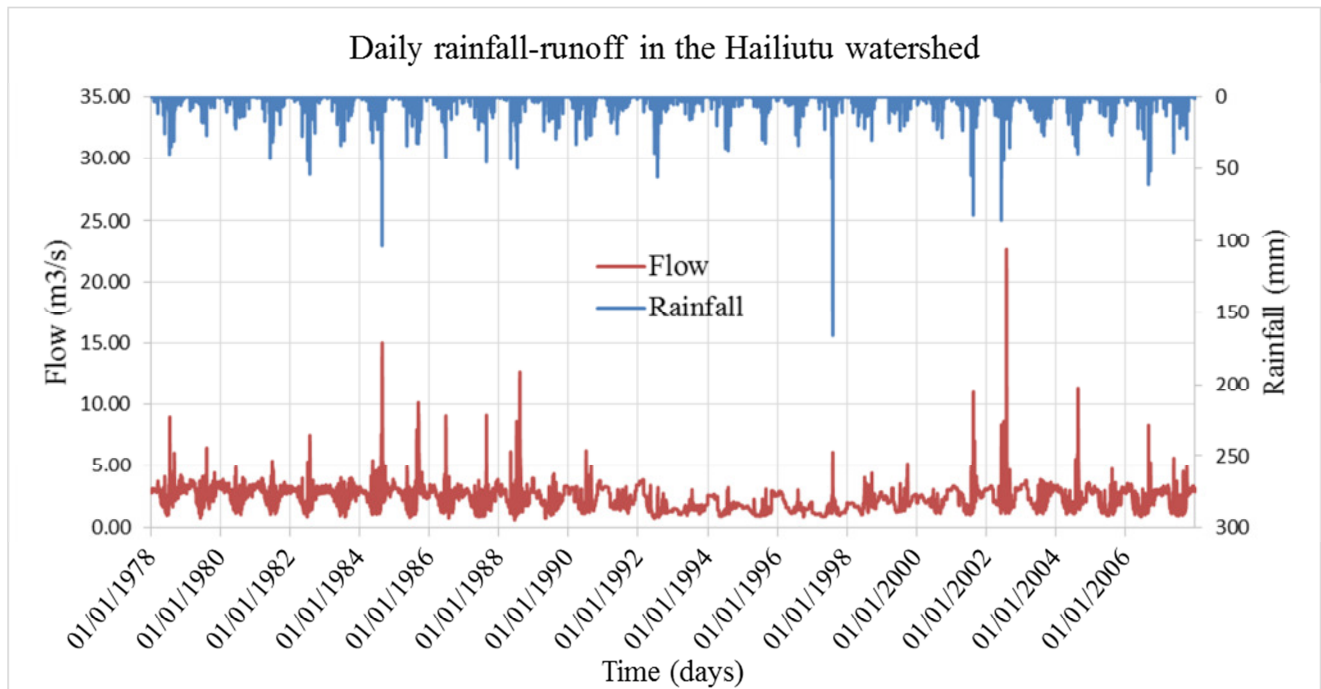


Fig. 2 Daily rainfall-runoff in the Hailiutu watershed

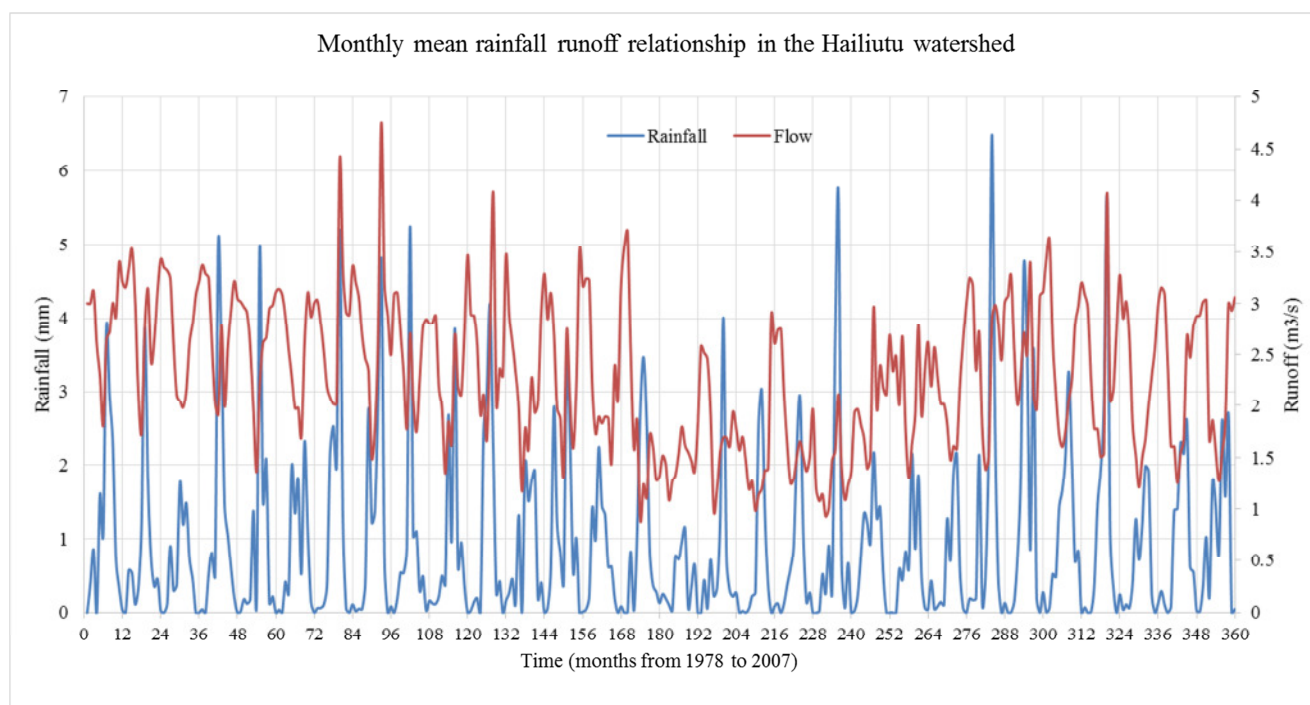


Fig. 3 Monthly mean rainfall-runoff relationship in the Hailiutu watershed

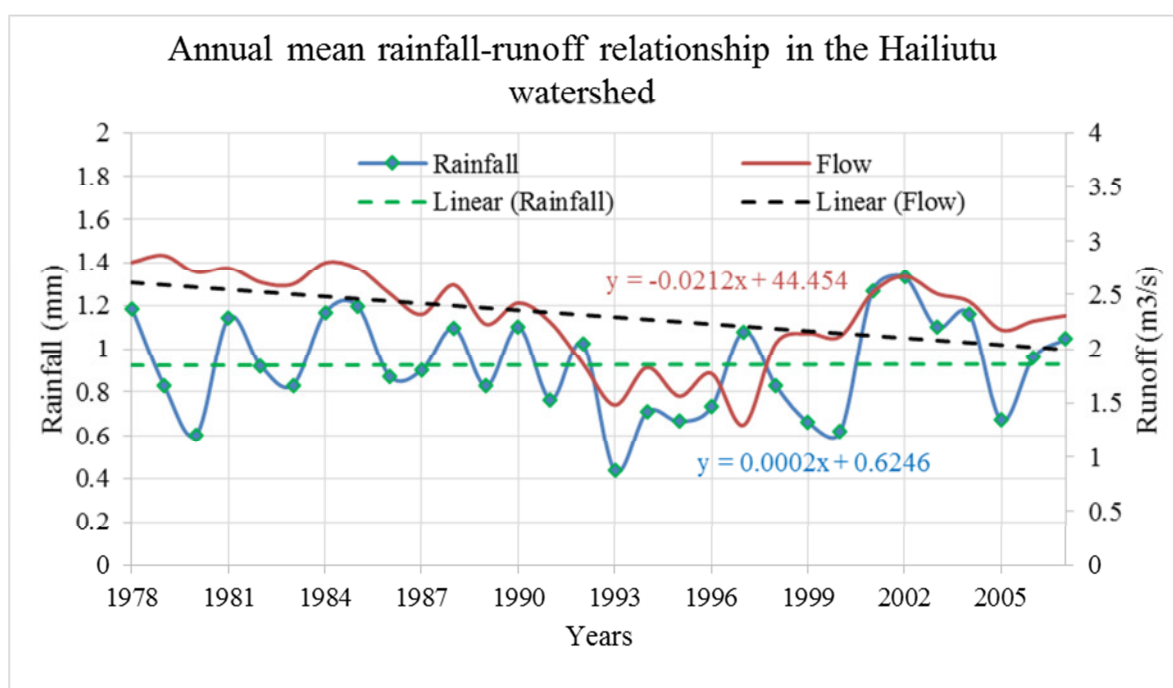


Fig. 4 Annual mean rainfall-runoff relationship in the Hailiutu watershed

The dashed lines show the linear trendline fitted to the annual mean data, the green shows rainfall trend, and the black line represents flow trend. The equation in red displays the trend equation of the flow trendline, while the blue shows the trend equation of rainfall trendline

Glancing at the daily and mean monthly rainfall and runoff in the Hailiutu watershed shows the baseflow contribution to discharge (Fig. 2 and Fig. 3): when rainfall is zero, discharge is never zero. However, from the same figures, it is also evident that high amounts of rainfall do not necessarily produce high flow. This could be due to the hydraulic engineering works in the watershed trapping most surface runoff, and then leaving the discharge at Hanjiamao station as mostly subsurface flow. This is [20] confirmed by observing that runoff in the Hailiutu watershed consists of 88% subsurface flow. The periods of low rainfall with high flows in Fig. 2 and Fig. 3 could be a result of outflow from the various hydraulic engineering works in the study's watershed. Moreover, the mean annual rainfall and runoff graph in Fig. 4 clearly shows the evidence and impact of the hydraulic engineering works in the study's watershed, so much so that while the linear trend of rainfall shows a minimal increase, runoff seems to follow a decreasing trend. Furthermore, without available data on the hydraulic engineering works in

the Hailiutu watershed for modeling purposes, we can conclude that less physically distributed models (like the HEC-HMS) would face challenges in simulating runoff for the study's watershed.

The Hailiutu catchment derived from HEC-GeoHMS in ArcMap was sub-divided into four sub-basins as displayed in Fig. 5.

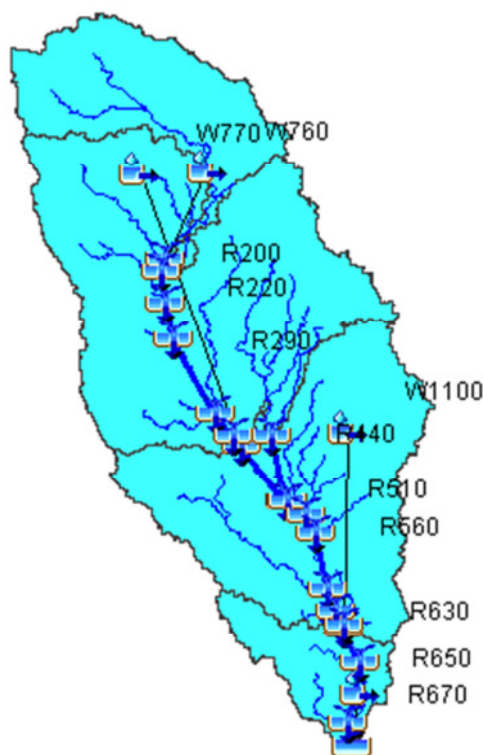


Fig. 5 The Hailiutu catchment derived from HEC-GeoHMS imported into HEC-HMS for runoff simulation

C. Calibration Results

We found that the model methodically underestimated winter and spring hydrographs, but it estimated some summer and autumn hydrographs more accurately. According to [33], this inaccuracy is connected to the difference between the nonlinear rainfall-runoff response in the watershed and the linear structure of the SMA model. Winter and spring flows signify low flows where base flow becomes the major source of runoff contribution in the Hailiutu watershed. According to [20], the annual mean discharge in the Hailiutu River comprises of roughly 88% groundwater discharge (on average). The underestimation of low flows means that the HEC-HMS model did not satisfactorily simulate the base flow contribution to runoff in the study's watershed. Fig. 6 illustrates the observed and simulated hydrograph for the calibration period. The black hydrograph indicates the observed runoff while the blue shows the model simulated runoff. The flow residual graph further demonstrates this result (Fig. 7), which clearly displays the underestimation of low flows (winter and spring flows). The flow residual graph (Fig. 7) also demonstrates underestimations of a number of summer flows. The simulation of runoff is time-biased, which increases errors in model performance assessments sensitive to outliers such as the root mean square error (RMSE) and the Nash-Sutcliffe Efficiency criteria. Tables 1 and 2 display the model simulation results and statistical performances. In Table 1, it can be seen that using the Nash-Sutcliffe efficiency as the calibration objective function resulted in underestimation of both the total flow volume and the peak flow. We therefore categorized the calibrated model performance for the Hailiutu watershed as unsatisfactory, in light of the negative Nash-Sutcliffe Efficiency results. The study's model was not validated due to unsatisfactory model performance statistics.

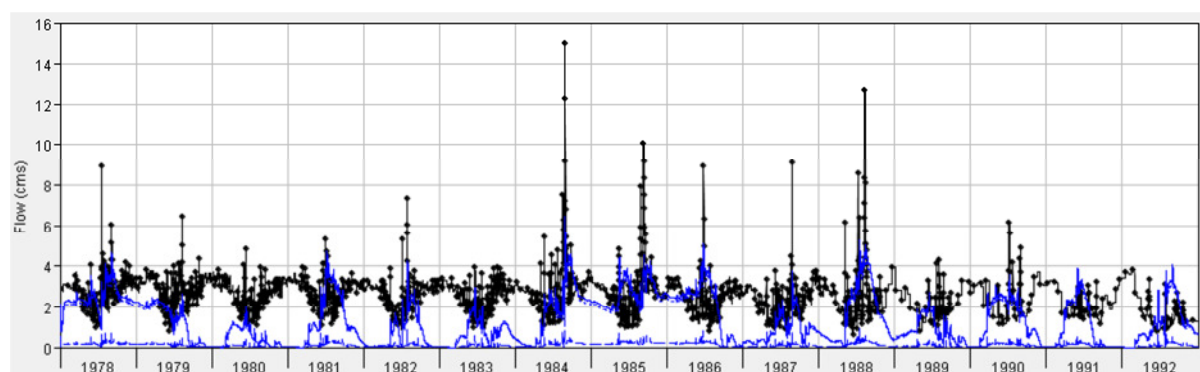


Fig. 6 The observed and simulated hydrograph for the 1978 to 1992 calibration period. The black color showing the observed runoff and the blue displaying the simulated runoff

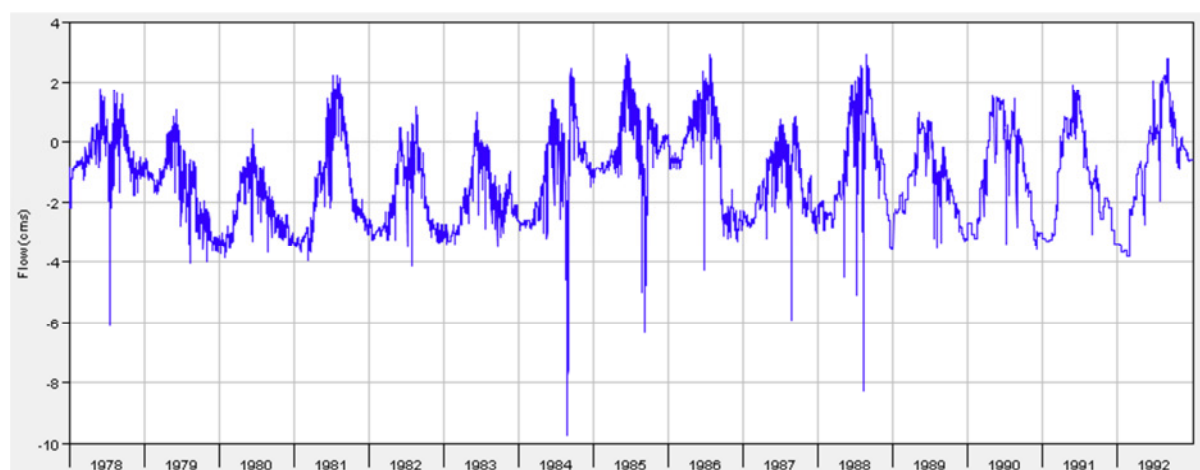


Fig. 7 Flow residual graph for the 1978 to 1992 calibration period

TABLE 1 MODEL SIMULATION RESULTS FOR 1978 TO 1992 CALIBRATION PERIOD

Variable	Observed	Simulated	Residual
Volume (m^3/s)	483.29	258.81	-224.48
Peak Discharge (m^3/s)	15.0	6.5	-8.5
Date of Peak Discharge	26Aug1984	27Aug1984	

TABLE 2 STATISTICAL PERFORMANCE FOR THE 1978 TO 1992 CALIBRATION PERIOD

Station	RMSE	MAE	PEPF (%)	PEV (%)	E
Outlet	1.9	1.6	-56.67	46.45	-3.45

IV. CONCLUDING REMARKS

This paper discusses runoff simulation in the Hailiutu watershed in northwestern China from 1978 to 2007. We investigated runoff simulation using GIS-generated watershed characteristics from HEC-GeoHMS and ArcHydro tools imported into HEC-HMS. The model was calibrated both manually and automatically using 15-year data from (1978-2007). We also used the univariate gradient search and Nelder Mead algorithms provided in the HEC-HMS program interchangeably. Our results demonstrated that the model generally underestimated winter and spring hydrographs, as well as a number of summer hydrographs, due to the discrepancy between the nonlinear rainfall-runoff response in the watershed and the linear structure of the SMA model. Overall, the continuous model of runoff in the Hailiutu watershed unsatisfactorily simulated runoff volume and peak runoff including the peak volume and time of peak. This could be explained by the model's poor base flow simulation, the unavailability of data on hydraulic engineering works in the study's watershed, and the inability of the continuous model to capture sub-basin-specific features due to its semi-distributed structure [33]. Given the unsatisfactory calibration results, we were unable to validate the model.

Ultimately, we discovered that watersheds with hydraulic engineering works pose a challenge to hydrological models in effectively simulating runoff without available data on such works. In order to better estimate winter and spring flows, we recommend further studies to simulate the seasonal runoff in the Hailiutu watershed.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Natural Science Foundation of China (NSFC) for generously providing the data used in this study.

APPENDIX A

A I AVERAGE MONTHLY EVAPOTRANSPIRATION (ET) ADOPTED IN THE METEOROLOGICAL MODEL

Month	W770 (mm/month)	W760 (mm/month)	W1320 (mm/month)	W1100 (mm/month)	Coefficient
January	5	5	5	5	0.7
February	5	5	5	5	0.7
March	5	5	5	5	0.7
April	20	20	20	20	0.7
May	20	20	20	20	0.7
June	125	125	125	125	0.7
July	125	125	125	125	0.7
August	125	125	125	125	0.7
September	125	125	125	125	0.7
October	20	20	20	20	0.7
November	20	20	20	20	0.7
December	5	5	5	5	0.7

APPENDIX B

B I CALIBRATED SMA PARAMETERS

Subbasin	Soil (%)	GW ^a 1 (%)	GW 2 (%)	Maximum Infiltration (mm/hr)	Impervious (%)	Soil Storage(mm)	Tension Storage(mm)
W770	10	0.658	2.17	27.536	1	540.842	0.262
W760	10	0.658	2.17	27.536	1	540.842	0.262
W1320	10	0.658	2.17	27.536	1	540.842	0.262
W1100	10	0.658	2.17	27.536	1	540.842	0.262
	Soil Percolation (mm/hr)	GW1 Storage (mm)	GW1 Percolation (mm/hr)	GW1 Coefficient (hr)	GW2 Storage (mm)	GW2 Percolation (mm/hr)	GW2 Coefficient (hr)
	0.058	0.021	0.622	19.404	3.324	0.014	10.112
	0.058	0.021	0.622	19.404	3.324	0.014	10.112
	0.058	0.021	0.622	19.404	3.324	0.014	10.112
	0.058	0.021	0.622	19.404	3.324	0.014	10.112

^a GW refers to groundwater

B II CALIBRATED CLARK TRANSFORM PARAMETERS

Subbasin	Time of concentration (hr)	Storage coefficient (hr)
W770	20	24
W760	20	24
W1320	10	14
W1100	14	20

B III CALIBRATED LINEAR RESERVOIR BASEFLOW PARAMETERS

Subbasin	GW1 (m3/s)	Initial	GW1 Coefficient (hr)	GW1 Reservoirs	GW2 Initial (m3/s)	GW2 Coefficient (hr)	GW2 Reservoirs
W770	0.5		5	1	0.05	50	5

W760	0.5	5	1	0.05	50	5
W1320	0.5	5	1	0.05	50	5
W1100	0.5	5	1	0.05	50	5

B IV CALIBRATED MUSKINGUM PARAMETERS

Reach	Muskingum K (hr)	Muskingum X	Number of subreaches
R180	12	0	1
R200	12	0	1
R220	12	0	1
R290	12	0	1
R310	12	0	1
R350	12	0	1
R370	12	0	1
R430	8	0	1
R440	8	0	1
R450	8	0	1
R470	8	0	1
R510	8	0	1
R560	8	0	1
R570	8	0	1
R590	8	0	1
R620	8	0	1
R630	6	0	1
R650	6	0	1
R670	6	0	1

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Meiling Wang received her Master's degree from Southeast University, China. She is a senior engineer at the Jiangsu Province Hydrology and Water Resources Investigation Bureau. She has been engaged in hydrological automation and water conservancy information technology for many years. She is an expert in the field of hydrologic data acquisition, communication, network, and application systems. Ms. Wang has performed research and explorations on the key technologies of hydrologic data acquisition, network management technology, data sharing, and application services. Many of her research findings have been applied in the construction of hydrology and water resources information systems, and they have achieved successful effects.

Lei Zhang is an engineer in the Department of Communication and Network at Jiangsu Province Hydrology and Water Resources Investigation Bureau. He received his B.Eng. degree from Nanjing University of Science and Technology (NUST), China and M.Sc. degree From Coventry University (CU), UK. He now serves as an IT engineer at Jiangsu Province Hydrology and Water Resources Investigation Bureau, where he engages in hydrological automation, as well as Communication and Network maintenance for the province-wide water conservation information technology systems. He has done research on hydraulic telemetering system and hydraulic modeling by IT for many years.

Thelma D. Baddoo is a doctoral degree student of Hydrology and Water Resources in the College of Hydrology and Water Resources in Hohai University in Nanjing, China. She received her B.Sc. degree in Civil Engineering in 2011 at the Kwame Nkrumah University of

Science and Technology in Kumasi, Ghana and M.Sc. degree in 2015 in Hydrology and Water Resources in Hohai University in Nanjing, China where her research is focused on the comparison of hydrological models for semi-arid regions.