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EVALUATION OF THE MIKE SHE MODEL FOR APPLICATION IN THE LOESS PLATEAU, CHINA[1]

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ABSTRACT: Quantifying the hydrologic responses to land use/land cover change and climate variability is essential for integrated sustainable watershed management in water limited regions such as the Loess Plateau in Northwestern China where an adaptive watershed management approach is being implemented. Traditional empirical modeling approach to quantifying the accumulated hydrologic effects of watershed management is limited due to its complex nature of soil and water conservation practices (e.g., biological, structural, and agricultural measures) in the region. Therefore, the objective of this study was to evaluate the ability of the distributed hydrologic model, MIKE SHE to simulate basin runoff. Streamflow data measured from an overland flow-dominant watershed (12 km^2) in northwestern China were used for model evaluation. Model calibration and validation suggested that the model could capture the dominant runoff process of the small watershed. We found that the physically based model required calibration at appropriate scales and estimated model parameters were influenced by both temporal and spatial scales of input data. We concluded that the model was useful for understanding the rainfall-runoff mechanisms. However, more measured data with higher temporal resolution are needed to further test the model for regional applications.

(KEY TERMS: Loess Plateau; MIKE SHE; model calibration and validation; China.)

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INTRODUCTION

Quantifying the hydrological responses to land use/land cover change and climate variability is essential for integrated sustainable watershed management, especially for water limited regions such as the Loess Plateau of the Yellow River Basin in northwestern China. Adaptive watershed management practices have been proposed and are being adopted

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around the world to address natural resource management challenges and uncertainty associated with increasing human disturbances and climate change. However, these adaptive approaches are largely dependent on our prediction accuracy and certainty of future conditions.

Predicting the impacts of land use/land cover, land management, and climatic change on the hydrological processes is especially challenging for the Loess Plateau region. The region contributes large amount of sediment to the middle reach of the Yellow River and has been significantly disturbed in the past century. Past studies suggest that the arid and semiarid regions are more sensitive than other geographical regions in China in terms of the effects of watershed management practices on water resource availability (Wang and Zhang, 2001; Zhang and Liu, 2005; Sun *et al.*, 2006; Wang *et al.*, 2006). In 1972, the Yellow River ran dry for the first time in recorded history. Drying has repeatedly occurred during the 1980s to 1990s with the longest dry-up time equaling 100 days. Each year, tremendous impacts on the aquatic ecosystems in the downstream area and water supply have been experienced in the basin (Su, 1996; Cheng *et al.*, 1998; Wang *et al.*, 2006). Afforestation efforts were identified as one of the possible reasons for reduced downstream runoff (Cheng *et al.*, 1998; Wang *et al.*, 2006; McVicar *et al.*, 2007). Several studies have suggested that watershed management can substantially affect the water resources in the region (He *et al.*, 2003; Huang and Zhang, 2004; Ran *et al.*, 2006; Sun *et al.*, 2006; McVicar *et al.*, 2007).

Large uncertainty and controversy on the effects of management on watershed hydrology remains in China due to the lack of long-term "paired watershed" experiments and the complexity of the watershed management issues (Ran *et al.*, 2006). Recent studies that used a rational or empirical modeling approach to assess land use and climatic variability impacts on water yield in the region were inconclusive, indicating that the hydrologic response to watershed management scheme and soil and water conservation measures are rather complex (Huang and Zhang, 2004; Ran *et al.*, 2006; Sun *et al.*, 2006; Li *et al.*, 2007; McVicar *et al.*, 2007; Mu *et al.*, 2007).

Physically based distributed models have many advantages compared with traditional lumped parameters models in simulating hydrologic response to forest management and global change (Sun *et al.*, 1998, 2007). Above all, distributed models can take into account of the spatial heterogeneity of watershed conditions. This is extremely important for watersheds with mixed land uses, such as the Loess Plateau region. In addition, distributed models can simulate the interactions among precipitation, geomorphology, vegetation, land use, and anthropogenic influences using Geographical Information Systems (GIS) and remote sensing technology (Ciarapica and Todini, 2002; Singh and Woolhiser, 2002).

The distributed watershed hydrologic simulation model, MIKE SHE originally derived from the SHE model (Abbott *et al.*, 1986a,b), has been widely used for examining hydrological responses to land use/land cover change and climate variability (Graham and Butts, 2005), operations of irrigation (Jayatilaka *et al.*, 1998; Singh *et al.*, 1999), hydrological manipulations for grass wetlands (Thompson *et al.*, 2004), forestry management and forest fire impact assessment (Lu 2006; McMichael and Hope, 2007), and for sustainable ground-water management (Demetriou and Punthakey, 1999). It has also been applied in more basic process studies including model structure and internal model assessment (Butts *et al.*, 2004; Christiansen *et al.*, 2004), and model uncertainty analysis (Christiaens and Feyen, 2001; Butts *et al.*, 2004; McMichael and Hope, 2007). Other areas of study on MIKE SHE include sensitivity analysis and spatial scale effects (Xevi *et al.*, 1997; V'azquez *et al.*, 2002; V'azquez and Feyen, 2007), model parameterization, calibration, and validation (Refsgaard, 1997; Andersen *et al.*, 2001; Henriksen *et al.*, 2003; Madsen, 2003), and evaluation of the potential evapotranspiration (PET) methods (V'azquez and Feyen, 2003). However, most of those studies were conducted in the temperate and humid climate conditions where shallow ground-water and surface water are tightly linked (Lu, 2006). Those sites are very different from the hydrological environments of the Loess Plateau of China (Sun *et al.*, 2007). The hydrologic processes of the Loess Plateau were dominated by overland flow, and ground water has little contribution to streamflow of small headwater watersheds.

Therefore, the overall objective of our study was to evaluate the applicability of the MIKE SHE model in a region where runoff generation is dominated by the overland flow processes. Our hypothesis was that a process-based, distributed hydrological model is capable to simulate the various aspects of the hydrologic cycle within a watershed. We tested the model's ability to replicate storm events and daily time scale hydrology. To our knowledge, this study represents the first effort that tests the MIKE SHE model in a semiarid region in China, and perhaps one of the few studies using a fully distributed hydrologic model for the Loess Plateau region.

METHODS

Watershed Characteristics and Hydrologic Measurements

The Luergou Watershed is located in the south of Tianshui City, Gansu Province in northwest China. The watershed has a total catchment area of 12 km^2 with an elevation ranging from 1,200 to 1,720 m (Figure 1). Average annual precipitation is about 570 mm of which over 80% occurs between May to October in the form of intense summer storms associated with a continental monsoon climate (Wang, 2007). The averaged soil erosion rate in the Luergou Watershed was estimated as 25 t/ha/yr during 1982-2000. The local soils are typically cinnamonic, clayey, and gray in color. The soils have a bulk density of about 1.26 g cm^{-3} and a porosity of 54%, with 43% of the soil particles less than 0.01 mm in diameter. High rainfall intensity and low infiltration capacity of the degraded soils on the watershed favored high soil erosion rates (Zhang and Liu, 2005).

Streamflow and precipitation have been monitored since 1983 by the Tianshui Soil and Water Conservation Experimental Station, the Yellow River Water Conservancy Committee, the Ministry of Water Resources of China. Precipitation data was collected by eight rain gauges located in the middle and lower parts of the watershed. Streamflow data were collected at the outlet of the watershed at a 10-min to 4-h time interval. Daily flow rates were determined by averaging all the measurements in a single day. Temperature data were acquired from the local meteorological station which was approximately 1 km away from the hydrologic gauging station.

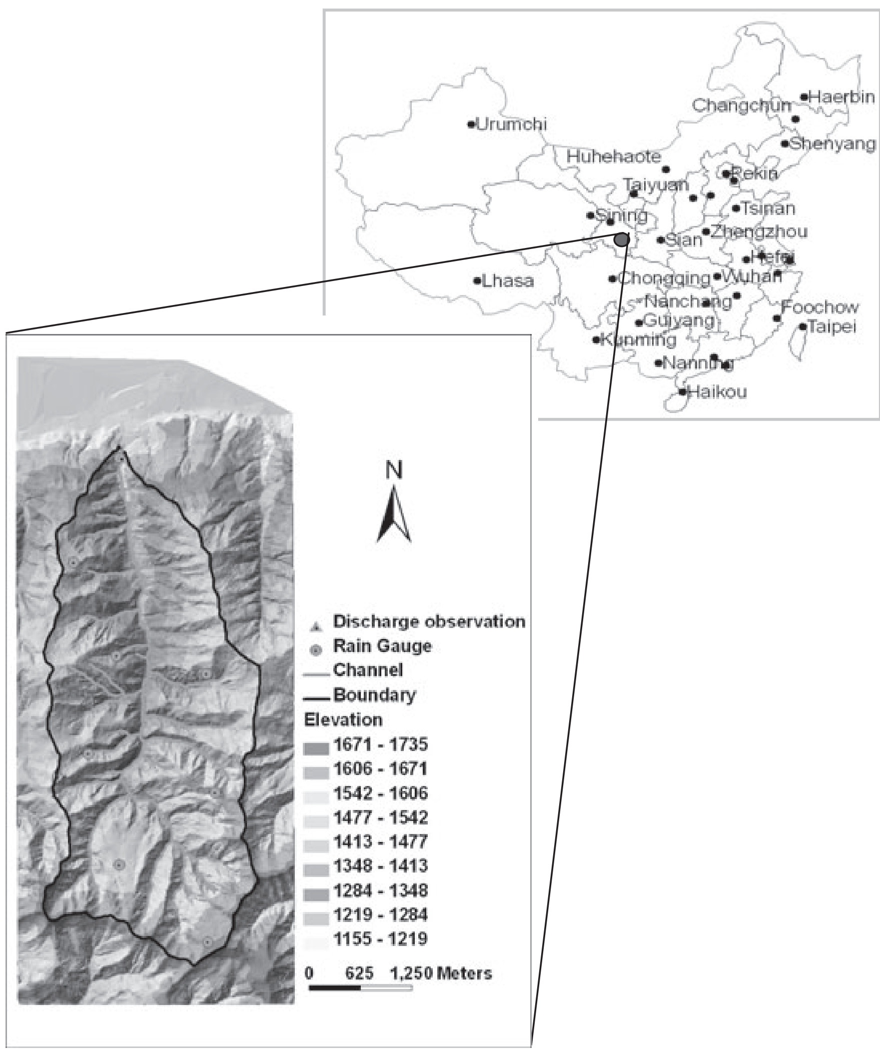

FIGURE 1. Location, Topography, Channel System, and Instrumentation Layout at the Luergou Watershed.

The MIKE SHE Model

There are numerous watershed-scale hydrologic models. The choice of models should be based on the objectives of use. Literature reviews suggest that the MIKE SHE/MIKE 11 modeling package (DHI, Hørsholm, Denmark) has several advantages over other hydrologic models for estimating watershed runoff: (1) it is a distributed model and most of the algorithms in describing the water movements are based a physical processes, (2) it simulates the overland flow processes commonly found in dry regions, and (3) it has been commercialized and a GIS user interface was built in the system that can directly use spatial GIS databases for model inputs. Also, the model has a strong visualization utility that makes interpretation of modeling outputs much easier.

MIKE SHE is a first generation of spatially distributed and physically based hydrologic model (Abbott *et al.*, 1986a,b). MIKE SHE simulates the terrestrial water cycle including evapotranspiration (ET), overland flow, unsaturated soil water, and ground-water movements. ET is modeled as a function of PET, leaf area index (LAI), and soil moisture content using the Kristensen and Jensen (1975) method. The unsaturated soil water infiltration and redistribution processes are modeled using Richard's equation or a simple wetland soil water balance equation. Saturated water flow (i.e., ground water) is simulated by a 3-D ground-water flow model. Channel flows and channel surface water and upland ground-water interactions are controlled by the MIKE 11 model, and by coupling of MIKE SHE and MIKE 11. MIKE 11 is a one-dimensional model that tracks channel water levels using a fully dynamic wave version of the Saint Venant equations. The coupling of MIKE SHE and MIKE 11 is especially important for simulating the dynamics of variable source areas in both wetland and upland watersheds. Detailed descriptions of the modeling procedures and mathematical formulation can be found in the MIKE SHE user's manual (DHI, 2004) and associated publications (Abbott *et al.*, 1986a,b; Graham and Butts, 2005).

Model Setup and Parameterization

Watershed Discretization. The Digital Elevation Model (DEM) data for model inputs were generated from a digitized 1:10,000 topographical map. Our initial analysis (Wang, 2007) indicated that a finer grid size (i.e., 10 or 30 m) keeps the modeling area close to the original watershed very well, but it did not successfully capture the peak flow observation due to the elongated river link with relative change of around 27%. While a coarser grid size (100 or 200 m) improved the peak flow simulation and kept the length of river link similar to the original, nevertheless it increases the modeling area by 11 and 21%, respectively (Wang, 2007). Therefore, the grid size for running the model was set as 50×50 m to compromise the simulation accuracy and physical characteristics of the watershed. The soil profile for the loess soil was assumed to be relatively uniform. According to the user reference of MIKE SHE (DHI, 2004), the vertical soil profile from the surface to 30 m was divided into a 10 cm interval for the upper most layer of 0-0.5 m, 25 cm interval for 0.5-2 m, and 50 cm interval for the layers deeper than 2 m, respectively. A complete list of model parameters is presented in Table 1.

Precipitation and Potential Evapotranspiration. We acquired rainfall records from eight automatic rain gauges. For simplification, a spatial distribution of precipitation model setup was defined as station based. The rainfall input was directly linked to each station and the controlled area for each station was determined by creating a Thiessen polygon using the terrace GIS tool. For annual rainfall runoff simulation, default values for the snowmelt component were used (e.g., snowmelt temperature 0°C and degree-day factor equal to 2 mm/day/°C (DHI, 2004). The uniform value of PET calculated by a temperature-based PET equation (Hamon, 1963) was used due to limitation of meteorological data.

Land Use and Land Cover. Land use surveys conducted in 1982, 1989, and 2002 indicated that the land use of the watershed has not changed significantly through the time period of this study (Wang, 2007; Wang *et al.*, this issue). Therefore, land use and land cover data of 1982 and 1989 were used for the model calibration and validation, respectively. Seasonal dynamics of LAI was specified according to the field measurement conducted in the summers from 2004 to 2006 with a LAI-2000 Plant Canopy Analyzer (LI-COR, Lincoln, Nebraska, USA) (Figure 2), and rooting depth was set up based on the previous study conducted in the region (Li, 2001). Preliminary analysis prior to model calibration suggested that discharge was insensitive to most of the ET parameters in the region. Therefore, default parameter values of $C1$, $C2$, $C3$, C_{int}, and A_{root} were used in calculating the actual ET (Kristensen and Jensen, 1975; DHI, 2004).

Unsaturated Zone. Soil samples were taken during the summers in 2004-2006 from the top 0.5 m layer of the all land use types and from the deeper layer below 0.5 m of the terraces. The soil water

TABLE 1. Parameter Setting for MIKE SHE Model With Procedure of Auto-Calibration.

Module	Parameter		Value/Range	Auto-Calibration
ET	$C1$		0.3	N
	$C2$		0.2	N
	$C3$ (mm/day)		20	N
	C_{int} (mm)		0.25	N
	A_{root} (1/m)		0.25	N
Unsaturated Zone (Ks in m/s)	Forestland	0-2 m	5e-008-5e-006	Y
		2 m below	1e-009 to 5e-007	Y
	Shrub and grassland	0-1 m	5e-008 to 5e-006	Y
		1 m below	1e-009 to 5e-007	
	Terrace	0-0.5 m	1e-009 to 5e-007	Y
		0.5 m below	1e-009 to 5e-007	Y
				Y
	Sloping cropland	0-0.5 m	1e-009 to 5e-007	Y
		0.5 m below	1e-009 to 5e-007	Y
	Non productive land	0-0.5 m	1e-009 to 5e-007	Y
		0.5 m below	1e-009 to 5e-007	Y
Overland Flow	Manning number/M [$m^{(1/3)}$/s]		20-40	Y
	Detention storage(mm)		2	N
	Initial water depth (mm)		0	N
Saturated Zone	Horizontal saturated hydraulic conductivity/ Ks_horizontal (m/s)		1e-007	N
	Vertical saturated hydraulic conductivity/ Ks_vertical (m/s)		1e-007	N
	Specific yield		0.5	N
	Storage coefficient (1/m)		0.0001	N
Channel Flow	Manning number/M [$m^{(1/3)}$/s]		25	N
	Leakage coefficient (1/s)		1e-006	N

Note: ET, evapotranspiration.

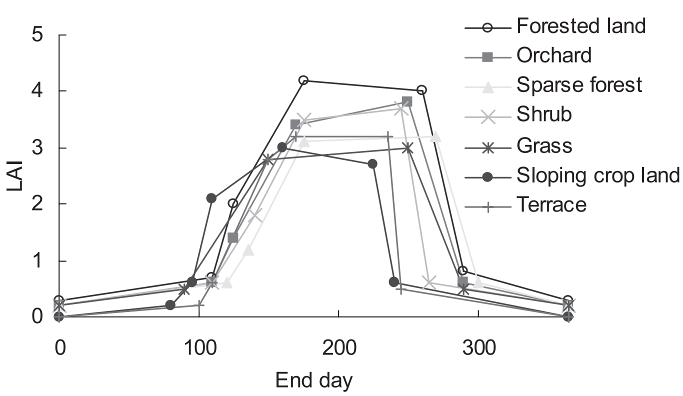

FIGURE 2. Leaf Areas Index (LAI) Dynamics for Various Land Uses.

retention curve for soil samples was determined using a No. 1500 15-bar Pressure Plate Extractor (Soilmoisture, Santa Barbara, CA, USA) in the laboratory. For forestlands, shrubs and grasslands, terraces, sloping croplands, and non production lands, Van Genuchten (1980) model was fitted using measured soil water retention curves for each soil layer from the surface to 0.5 m. For deeper soil layers below 0.5 m, measured soil water retention curve for terraces were applied across all land uses assuming a uniform soil texture. Saturated soil hydraulic conductivity (Ks) values were found from published literature in the study region (Luo *et al.*, 2003; Stolte *et al.*, 2003; Zhang *et al.*, 2005a; Ran *et al.*, 2006).

Saturated Zone. The ground-water depth was approximately 50 m in the study watershed, and thus base flow contributed very little to streamflow. Therefore, we assumed the distribution of soil parameters such as horizontal saturated hydraulic conductivities (Ks_h), vertical saturated hydraulic conductivities (Ks_v), specific yield, storage coefficient, and drainage time constant were uniform across the watershed (Henriksen *et al.*, 2003; Madsen, 2003). Our sensitivity analysis indicated that simulated peak flow and total surface flow changed by 1 and 12%, respectively, when Ks_h varied from 1e-008 to 1e-006. In addition, changes in the vertical saturated hydraulic conductivity (i.e., Ks_v), the specific yield, and the storage coefficient did not make any difference for peak flow and surface flow simulations. This was expected because there was little interaction between surface and ground-water flows at the study watershed.

Overland Flow and Channel Flow. The streamflow was dominated by surface flow, and parameter of

Manning number (M) was found to be sensitive for the simulation. Therefore, Manning number (M) was subject to auto-calibration. Channel discharge and water level can be dynamically simulated by coupling MIKE SHE and MIKE 11. The drainage network that consists of 27 channels including first-order, second-order, and third-order ephemeral streams were extracted from a digitized terrain map at 1:10,000 scale. Cross-section for each channel in model setup was generally specified according to the field investigations. Uniform initial Manning number (M) for all channels was set as 25 $m^{1/3}/s$ (Fu *et al.*, 2002) and the channel leakage coefficient was set as 1e-006/s (Henriksen *et al.*, 2003; DHI, 2004).

Simulation Time Steps. Due to the coarse resolutions of rainfall and runoff data, the initial time step for storm events model and annual scale model was set as 4 and 24 h, respectively. MIKE SHE has the flexibility of using variable simulation time steps in modeling different hydrologic components and flow characteristics (Demetriou and Punthakey, 1999). Therefore, for the event scale model, the maximum time step for the saturated zone component was set as 12 h to reduce the computation time in view of the less importance of saturated flow in the watershed, and the maximum time steps for other components (e.g., overland flow, unsaturated flow, and ET) were specified as 4 h as the initial time step.

Initial Conditions. Initial values for several state variables such as soil moisture content and ground-water level affect model performances greatly (Refsgaard, 1997), especially for simulating storm hydrographs. Deep ground-water levels, very low base flow, and low soil moisture content were some of the characteristics in our study region. We applied the "hot start" utility provided by MIKE SHE to generate the initial conditions before simulating storm events by simulating the 15-day rainfall runoff process. We generated the initial conditions for the annual runs by simulating one whole year prior to model calibration and validation.

Model Performance Evaluation Methods

Theoretically, parameters for a physical based distributed hydrological model are all measurable in the field. Yet, model calibration is usually a necessary step to derive the "effective" parameters for the entire watersheds or individual modeling element (Madsen, 2003). We evaluated the model performance by visual inspection of the simulated *vs.* observed discharge hydrographs (Jayatilaka *et al.*, 1998; Christiansen *et al.*, 2004). In addition, four quantitative criterions including coefficient of correlation (R), coefficient of determination (CD), root mean square errors (RMSE), and mean streamflow simulating error, F_{Bal} were used to evaluate the model performances on both the storm event of subdaily time scale and continuous simulation on a daily time scale (Xevi *et al.*, 1997; V'azquez and Feyen, 2002; Henriksen *et al.*, 2003).

$$R = \frac{\sum_{i=1}^{n}(O_\mathrm{i} - \overline{O})(S_\mathrm{i} - \overline{S})}{\sqrt{\sum_{i=1}^{n}(O_\mathrm{i} - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(S_\mathrm{i} - \overline{S})^2}} \quad (1)$$

$$\mathrm{CD} = \frac{\sum_{i=1}^{n}(O_\mathrm{i} - \overline{O})^2}{\sum_{i=1}^{n}(S_\mathrm{i} - \overline{O})^2} \in (0, +\infty) \quad (2)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_\mathrm{i} - S_\mathrm{i})^2} \quad (3)$$

$$F_{\mathrm{Bal}}(\%) = 100 \times \frac{(\overline{O} - \overline{S})}{\overline{O}}, \quad (4)$$

where O_i measured streamflow(m^3/s); S_i simulated streamflow(m^3/s); $\overline{O}$ measured mean streamflow (m^3/s); and $\overline{S}$ simulated mean streamflow (m^3/s).

Those four measures of model performance reflect the different aspect of goodness of fit. The correlation coefficient was called the goodness of fit (Legates and McCabe, 1999), reflecting the degree of the similarity for the patterns between the simulated and observed hydrographs. CD value represents the ratio of the scatter of simulated and the measured values around the average of the observations (V'azquez *et al.*, 2002). F_{Bal} indicates general streamflow simulation capability (Henriksen *et al.*, 2003). The RMSE criteria were used for auto-calibration.

Due to the high intensity of the rainfall in this region, the hydrologic processes were governed by the overland flow mechanism (Ran *et al.*, 2006), and the total annual water yield of the watershed was produced from several thunder storms. Furthermore, the runoff coefficient of the studied watershed was very low throughout the monitoring period (Wang *et al.*, this issue), therefore, the dataset from 1983 to 1984 and 1989 to 1990 with higher rainfall and runoff amount were selected to run the model for calibration and validation, respectively. Both time periods were wet years with average annual precipitation of 773 and 701 mm, and the average daily temperatures were 10.2°C and 10.9°C, respectively (Wang *et al.*, 2006).

In addition, we also used a subdaily time step to simulate the storm-flow processes. Flood duration curve analysis indicated that the peak flow for the frequency greater than 80% was 1.19 m^3/s (Zhang *et al.*, 2005b). Therefore, three storm events, September 7th of 1983, September 27th of 1983, and August 16th of 1983 which had peak flows ranging from 0.5 to 1.5 m^3/s were chosen to calibrate the subdaily process. Seven storms with a similar magnitude of peak flow and one with an extreme value (Table 2) were used to validate the model. Both annual scale model and storm event models were calibrated against discharge by the auto-calibration procedure with RMSE as an objective function. During auto-calibration, parameters are adjusted automatically according to a specific search scheme for optimization of certain calibration criteria (objective functions). Detailed procedures are found in Madsen (2003).

RESULTS

Model Calibration and Validation for Daily Flows

Hydrographs for the model calibration and validation periods show that the annual model could capture the dominant runoff process and streamflow dynamics of the small watershed (Figure 3). However, the model both overestimated and underestimated streamflow during the simulation period (Figures 3A and 3B). Reasonable coefficients of correlation R of 0.83 and 0.63 and RMSEs of 0.06 and 0.05 for model calibration and validation period were obtained. The mean streamflow simulating error for model calibration (F_{Bal} = −40.0%) was much higher than that for model validation (F_{Bal} = −17.9) even though R for the calibration was higher than that for validation. The higher coefficient of correlation R = 0.83 between modeled and measured discharge during calibration period was mainly due to the fact that fewer flow events with high peak flows were underestimated and less modeling errors occurred. For instance, the simulated and observed highest peak flows in August 3, 1984, were 1.9 and 1.6 m^3/s, respectively, during the calibration period The simulation error was only −14%. For the validation period, peak flow rates for a few more events were underestimated or overestimated and resulting in much higher simulation errors. The observed and simulated peak flows on September 7, 1990, were 0.5 and 0.3 m^3/s, respectively, indicating a much higher simulation error (i.e., −34%) than that of the calibration period. Much higher simulation errors of 6 and 92% were found for the events of June 13, 1989 and August 18, 1989, respectively.

Model Calibration and Validation for Storm Events

The model matched the general storm-flow patterns and the time to peaks for the selected storms used for both calibration (Figures 4A-4C) and validation (Figures 5A and 5B) periods. The correlation coefficients between predicted and measured flows for the calibrations for events of August 16, 1983, September 7, 1983, and September 27, 1983 were 0.73, 0.81, and 0.83, respectively. Those values were considered rather high for storm event simulations. However, CD for these three events during the calibration period were 0.39, 0.71, and 0.50, respectively. The F_{Bal} values were all higher than 20% indicating that the model could not simulate the average flow as well. Details of statistics for model validations for eight storm events were presented in Table 2. Most of coeffi-

TABLE 2. Statistics of Storm Event Modeling for Selected Storm Events.

	Storm Event	**CD**	***R***	**RMSE**	F_{Bal} **(%)**	***P*** **(mm)**	Q_{Peak_O} **(m^3/s)**	Q_{Peak_S} **(m^3/s)**
Calibration	September 7, 1983	0.707	0.805	0.1559	38.58	32	0.874	0.789
	September 27, 1983	0.502	0.834	0.3478	33.56	58	1.420	1.401
	August 16, 1983	0.391	0.732	0.1693	−38.48	62	0.593	0.947
Validation	June 21, 1984	1.449	0.799	0.7763	41.84	71	2.94	1.769
	July 25, 1984	0.913	0.496	0.4903	62.65	39	1.980	1.636
	September 7, 1985	0.252	0.759	0.2970	−0.71	42	1.150	1.511
	September 14, 1985	0.395	0.981	0.1927	36.16	23	0.675	0.825
	October 15, 1985	0.868	0.723	0.1226	−30.12	35	1.060	0.777
	July 9, 1985	0.187	0.567	0.0857	−53.72	29	0.411	0.646
	June 25, 1987	0.093	0.923	0.2471	8.43	75	0.786	1.508
	July 25, 1985	1.581	0.801	11.6838	90.40	17	22.4	2.879

Notes: CD, coefficient of determination; RMSE, root mean standard error.

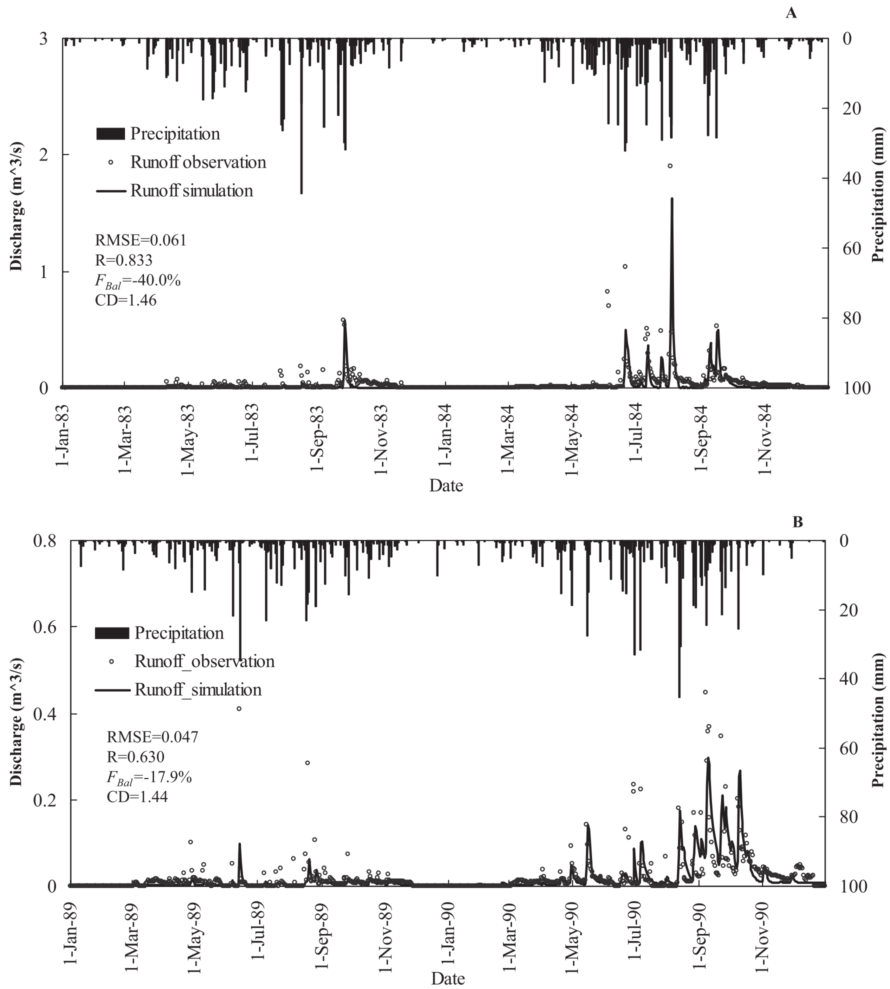

FIGURE 3. Precipitation and Annual MIKE SHE Model at Daily Time Scale Calibration (A) and Validation (B) Showing RMSE (root mean standard error), R (coefficient of correlation between measured and simulated daily streamflow), F_{Bal} (simulating errors for average streamflows), and CD (coefficient of determination).

cients of correlation were found acceptable, but CDs and F_{Bal} varied greatly among the simulated events. For the extreme magnitude of event, July 25th of 1985, $R = 0.80$, while CD and F_{Bal} were 1.6 and 90.4%, respectively. Again, validation results show that the model could simulate the general hydrological processes even though the model could overestimate (Figure 4B) or underestimate (Figure 4A) peak flows and volumes.

Parameters Calibrated

The saturated hydraulic conductivity for the unsaturated zone and Manning coefficient for modeling overland flow were the two most sensitive parameters for this study. The derived saturated hydraulic conductivity values for the top soil layer in the unsaturated zone through calibration by the storm event model and annual model for the same land use were quite different (Table 3). We found that the saturated hydraulic conductivity calibrated by the storm event model for forestland (i.e., 0-2.0 m) and shrubland and grassland (i.e., 0-1.0 m) were higher than that calibrated by the annual model. Saturated hydraulic conductivity calibrated by the storm event model for terrace, sloping agricultural land, and non productive land within the top soil layer were less than that calibrated by the annual model. Manning coefficients of overland flow calibrated for storm event model and annual model were 0.05 and 0.03, respectively. This may indicate that modeling overland flow at the finer scale resulted in higher roughness than at a coarser time scale, and thus the temporal scale effect is important for model performance. Higher saturated hydraulic conductivity (Ks) of vegetated lands resulted in lower overland flow than other land uses with lower Ks. This may have important implications

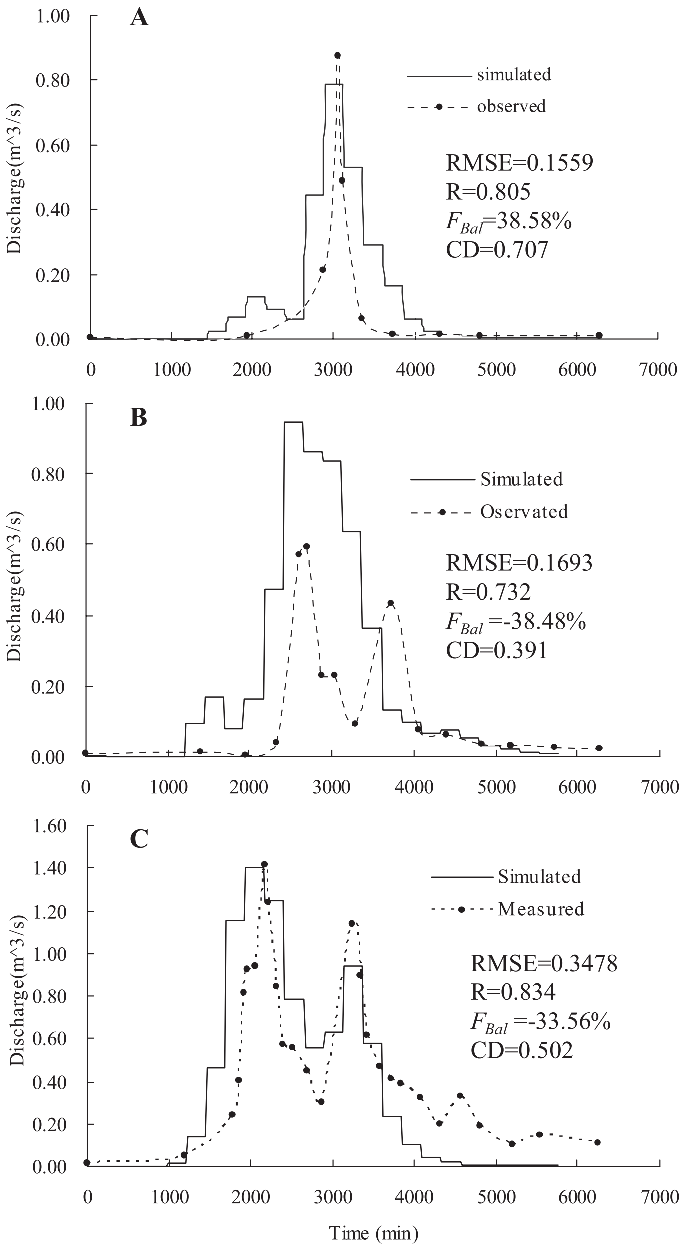

FIGURE 4. Calibration of Storm Event Model (A) Event of 7 September 1983, (B) 16 August 1983, and (C) 27 September 1983.

to the local revegetation efforts in reducing soil erosion.

DISCUSSION

Hydrographs measured at the watershed outlet in the semiarid regions are the synergistic outcomes of many key interacting processes that control the watershed hydrology such as rainfall, infiltration, overland flow, and flow routing in various channels. To simulate those processes for a watershed with mixed land uses and a complex terrain, this study found that the MIKE SHE had to be calibrated to produce a reasonable hydrograph. As discussed below, several key factors affect the matches between simulated by MIKE SHE and measured hydrographs.

Temporal Scale Effects on Model Parameter Determination

Past modeling studies suggested that the most sensitive parameters for watersheds dominated by infiltration-excess flow generation are those that control the infiltration and overland flow routing processes (Senarath *et al.*, 2000; Downer *et al.*, 2002). Davis *et al.* (1999) demonstrated that soil saturated hydraulic conductivity measured by different methods could be different by 1 to 3 orders of magnitude. Many researchers have evaluated impact of varying spatial resolution, and it is widely accepted that calibrated parameters are effective for a particular spatial scale (Wood *et al.*, 1988; V'azquez *et al.*, 2002, V'azquez and Feyen, 2007). Our study suggested that the effective parameter was not only dependent on the spatial scale, but also dependent on the temporal scale. Therefore, the optimization of the temporal-scale dependent parameters also was a key process for successful hydrological modeling watersheds on the Loess Plateau in Northwest China.

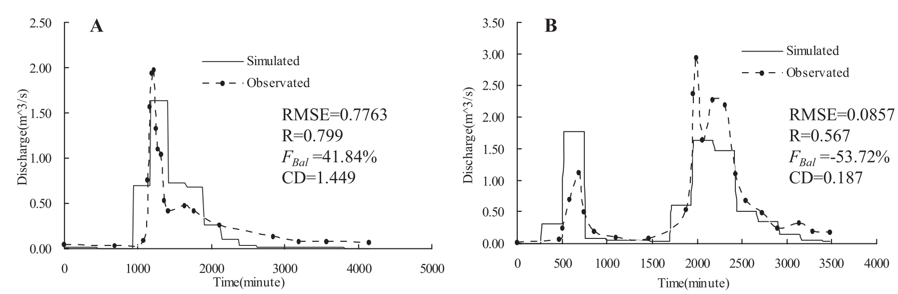

FIGURE 5. Validation of Storm Event Model (A) Event of 21 June 1984 and (B) 9 July 1987.

TABLE 3. Auto-Calibrated Parameters for Event and Annual Models.

Module	Parameter	Soil Depth (m)	Values		
			Storm Event	Annual	Range
Unsaturated Zone Ks, m/s	Forested land	0-2.0	9.92e-007	2.05e-006	5e-008 to 5e-006
		>2.0	3.89e-008	4.58e-009	1e-009 to 5e-007
	Shrub and grassland	0-1.0	8.84-007	3.98e-006	5e-008 to 5e-006
		>1.0	3.89e-008	4.58e-009	1e-009 to 5e-007
	Terrace	0-0.5	3.89e-008	6.20e-009	1e-009 to 5e-007
		>0.5	3.89e-008	4.58e-009	1e-009 to 5e-007
	Sloping agricultural land	0-0.5	1.83e-007	1.67e-007	1e-009 to 5e-007
		>0.5	3.89e-008	4.58e-009	1e-009 to 5e-007
	Non productive land use	0-0.5	3.12e-007	2.56e-007	1e-009 to 5e-007
		>0.5	3.89e-008	4.58e-009	1e-009 to 5e-007
Overland Flow	Manning number/M [$m^{(1/3)}$/s]		36.3	22.4	20-40

Effects of Hydrologic Processes on Model Performance

The annual scale MIKE SHE model performed better in simulating the general hydrograph patterns than modeling the total water yield and the average flow rates as indicated by the various performance criteria. Model performance may be influenced by the underlining runoff generation mechanisms as determined by the interactions between rainfall amount and intensity, antecedent soil moisture, vegetation, topography, and geology (Beven, 2002; Ciarapica and Todini, 2002). It is critically important to understand the runoff production mechanisms for physically based distributed watershed hydrologic model development and applications to produce realistic model predictions (Downer *et al.*, 2002; V'azquez *et al.*, 2007). Our model analysis suggested that a daily time step scale model was not sufficient to capture the very quick response of runoff in a watershed that was dominated by infiltration-excess overland flows. The calibrated daily time step model could simulate the saturation-excess runoff better during the dry period under big storm conditions than infiltration-excess runoff. For instance, the storm-flow events (peak flow 0.4-0.7 m^3/s) on June 5, 1984, and June 13, 1989, corresponded to high rainfall intensities (Table 4), while the simulated peak flow for these two events were lower than 0.1 m^3/s. We believe that the application of aggregated daily rainfall moderated the influence of the high rainfall intensity, resulting in the lower runoff estimation. In addition, large antecedent precipitation might have offset the deficiency of aggregated rainfall, and thus the estimated runoff for August 3, 1984, and September 27, 1983, with large antecedent rainfall having the same magnitude as the observation (Table 4). Improved daily streamflow modeling during the period of higher antecedent rainfall conditions suggested that MIKE SHE could simulate saturated overland flow better than during dry spells with big storm conditions. Other modeling

TABLE 4. Comparison Between Simulated and Observed Runoff for Selected Time Period in Annual Scale Model.

Period	Modeled Runoff (m^3/s)	Observed Runoff (m^3/s)	Rainfall (mm)	Rainfall Intensity (mm/h)	Antecedent Rainfall (mm) (7 days)
June 5, 1984	0.003	0.702	24.4	15	13.5
June 13, 1989	0.098	0.409	34.7	Not available	33.4
August 3, 1984	1.624	1.9	24.7	10	61.8
September 27, 1983	0.575	0.578	24.4	12.4	82.3

studies for overland flow-dominated watersheds also suggested that models were not very sensitive to saturated hydraulic conductivity in unsaturated zone for large rainfall-runoff events (Ogden and Julien, 1993; Woolhiser *et al.*, 1996).

Effects of Model Setups

Although the time step for the storm event model should be as fine as possible in order to produce reasonable hydrographs to compare, calibrate, and validate the model (Bergstrom *et al.*, 2002; V'azquez *et al.*, 2002), the calibration and validation of the storm event model was not necessarily better than the annual streamflow simulation as demonstrated in our study. The effect of temporal and spatial scales (i.e., time step and grid size) of model setup is one of important factors influencing model performances (V'azquez *et al.*, 2002). The time step is normally set to the same resolution as the discharge measurements when continuous fine-scale measurements are not available (Ciarapica and Todini, 2002; Downer *et al.*, 2002). In our study, only 20% of runoff flow data were measured at an interval from 15 min to 4 h and the other 80% with much coarser time intervals. The data problem made it very difficult to set up a proper time step for model calibration and validation. We suspected that the data resolutions had indirect effects on the model calibration and validation results. Therefore, runoff overestimation and underestimation could be possible when calibrated parameters from one time step were used for validation purposes when the data were measured at a different time interval.

As mentioned previously, using a daily time step to calibrate and validate the model might give large errors for infiltration-excess overland flow dominated watersheds. Finer time step and rainfall datasets with a higher temporal resolution should be used in this region to simulate the watershed hydrology sufficiently. However, it should be emphasized that the simulation of the storm event model will not necessarily be improved given the coarse resolutions input and the inevitable potential errors associated with the precipitation and the PET estimation (Andersen *et al.*, 2001; V'azquez and Feyen, 2003). It was reported that the method of calculating PET has significant effects not only on the optimization of some ET model parameters in MIKE SHE but also on the model performances in terms of streamflow prediction (V'azquez and Feyen, 2003). Although a spatially distributed rainfall input was applied throughout the whole model exercises, uniformed PET values estimated by the temperature-based Hamon method for all land uses might also contribute to the simulation errors.

CONCLUSIONS

The MIKE SHE hydrologic simulation model was calibrated and validated with measured streamflows at a storm event subdaily and continuous daily scales. This modeling exercise clearly identified deficiency of field data and research gaps The MIKE SHE could simulate the overland runoff generation mechanisms that occurred in the study watershed, but the model had large simulation errors for some individual storm events. Model performance for storm events was not as satisfactory as for the continuous daily streamflow simulation. To further test the model performances in the study region, it is essential to continuously measure the rainfall and streamflow at finer temporal scale. Moreover, better estimation of PET is important as well. Model uncertainty analysis using the Generalized Likelihood Uncertainty Estimation (GLUE) method (Butts *et al.*, 2004) would be required in the future to better understand the hydrologic processes.

This modeling study demonstrated that the well-recognized "equifinality" phenomenon of a physically based distributed hydrological model plays a significant role in affecting model performance. Different sets of parameters are needed to construct models for different purposes (e.g., storm hydrograph *vs*. long-term water balance studies). Integrated watershed management practices to reduce soil erosion and sedimentation in the Loess Plateau of northwest China usually include biological measures (e.g., forestation) and structural measures (e.g., terraces and check dams). The complex land use and management practices further challenge watershed hydrological modeling. This study focused on land use types in model parameterization and few studies have been conducted to quantitatively develop the relationships between structural measures and model parameters. Understanding the coupling impacts of soil and water conservation measures and rainfall regimes on the runoff generation mechanisms and their quantitative linkages with hydraulic parameters could further improve the MIKE SHE model application in the region.

In addition to land use change, climate in the study has showed a warming trend in recent decades. The physically based MIKE SHE has a great potential to be used to evaluate the coupling effects of future soil conservation practices and climatic change and variability on watershed hydrology at multiple scales.

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