

## **Development of a coupled land-surface and hydrology model system for mesoscale hydrometeorological simulations**

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**Abstract** In this study, the coupled land-surface and hydrology model system (Noah LSM-HMS) was developed; it couples the Noah land-surface model (Noah LSM) with the large-scale hydrological model system (HMS). Detailed hydrological processes, such as unsaturated-zone soil moisture dynamics, river/lake–vadose and river/lake–groundwater exchange, streamflow routing, groundwater-table depth and horizontal groundwater flow are explicitly considered in this system. It is designed for interactive meteorological and hydrological simulations driven by a mesoscale meteorological model such as the Weather Research and Forecasting (WRF) system. Subsequently, Noah LSM-HMS was applied for streamflow simulations using the routine meteorological observations at 10-km resolution in the Chishui watershed in China. Results show that the streamflows calculated at the watershed outlet and two upstream hydrological stations are in reasonable agreement with those observed. Large differences between the simulated and observed streamflows still exist due to probable errors in the model structure and the meteorological forcings, especially the precipitation data.

**Key words** land-surface model; large-scale hydrological model; runoff

### **INTRODUCTION**

Water bodies, such as rivers, lakes, groundwater, wetlands and glaciers, play a very vital role in climate systems (Yu *et al.*, 2006). On one hand, climate change affects these water bodies in many ways. Thus floods, droughts, decline of groundwater table levels, and retreat of glaciers and wetlands are important indicators of past climate change. On the other hand, these changes of water bodies have crucial feedbacks on climate. For instance, the spatial distribution of surface soil moisture, to a great extent, influences the radiative transfer between land surface and atmosphere. In order to better depict the physical and chemical processes of climate systems, climate models or meteorological models should not only have sound parameterization schemes for gas, aerosol, cloud, radiation, transport and meteorological processes, but also include a rational land-surface model that computes surface energy fluxes, soil and vegetation temperature updates, snowpack, snowfall and snowmelt processes, and especially surface water fluxes and soil water dynamics. To explicitly include within a climate or meteorological modelling system, detailed hydrological processes such as river routing and discharge, river–vadose and river–groundwater exchange, lake extents and depths, and groundwater flow, it is necessary to couple a global climate model (GCM), a limited-area regional climate model (RCM) or a mesoscale meteorological model with a distributed physically-based hydrological model.

This study describes a method of interactively coupling a land-surface model with a physically-based large-scale hydrological model. This new coupled land-surface and hydrological model, Noah LSM-HMS, was applied for mesoscale hydrometeorological simulation over the Chishui watershed in China. The model description, data preparation and application of the Noah LSM-HMS model are described here.

### **MODEL DESCRIPTION**

The method described below couples a mesoscale meteorological model on a meso-sized grid to a hydrological model on the same grid, as shown in Fig. 1. The atmospheric component can be a

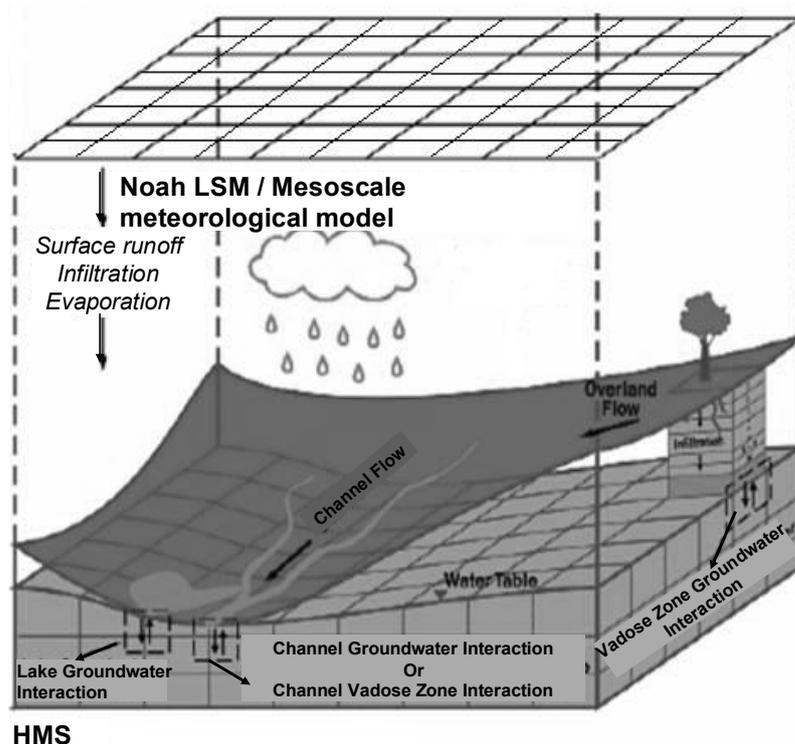


Fig. 1 Sketch of Noah LSM-HMS.

mesoscale meteorological model, such as the Weather Research and Forecasting (WRF) system, or gridded meteorological data sets plus a land-surface model. In this study, the WRF model was not adopted; instead, we used the observed meteorological data to drive the Noah land-surface model (Noah LSM) as the atmospheric component. The hydrological component should be a distributed hydrological model that describes detailed hydrological processes such as interactions among unsaturated soil water, groundwater, river water and lake water. In this way, a coupled system Noah LSM-HMS is developed, which is composed of two components: the Noah land-surface model (Noah LSM) and the Hydrologic Model System (HMS) (Fig. 1).

Noah LSM is an extended version of the Oregon State University land-surface model (OSULSM) (Chen & Dudhia, 2001), and it is included in the mesoscale meteorological model Weather Research and Forecasting (WRF) system as the land-surface module. Noah LSM simulates a single vertical column of vegetation, snow and soil at each land grid cell. Radiative fluxes, turbulent fluxes of momentum, sensible heat and evapotranspiration are calculated at each time step. In the vertical soil column, physical processes such as heat diffusion, unsaturated liquid water transport, saturated gravitational drainage, local surface runoff, bottom drainage, uptake of liquid water by plant roots for transpiration, and freezing and thawing of soil ice are calculated in Noah LSM.

The HMS is a large-scale hydrological model which is based on the earlier Hydrologic Model System (Yu, 2000). It explicitly predicts unsaturated-zone soil moisture, river–vadose and river–groundwater exchange, streamflow routing, groundwater-table depth and horizontal groundwater flow. Similar to most large-scale hydrological models, HMS supposes that only one major river exists in each grid cell and minor streams convey surface runoff into this river. For groundwater and vadose zone hydrology, a one-layer aquifer is assumed in HMS, representing a single bedrock unit extending from the surface to a depth of tens to a few hundred metres with an impervious base. Above the groundwater table, the unsaturated soil moisture profile in the vadose zone is assumed to be stable, with downward gravitational drainage balanced by upward vertical diffusion. The water flux through the aquifer is expressed by the 2-D Boussinesq equation, which includes

calculation of the horizontal groundwater flow, channel–vadose and channel–groundwater fluxes depending on the depth of river bed, water head and surface water level. The change of river and lake water is formulated by a 2-D diffusive wave equation, depicting the river flow routing, depth and extent of lake, and interaction between the surface water and groundwater (Yu *et al.*, 2006).

Both Noah LSM and HMS are driven on 10-km grid cells in this study. The gridded observed meteorological data, such as air temperature, air relative humidity, surface pressure, wind speed, surface downward long-wave radiation, surface downward solar radiation and precipitation, were used to feed Noah LSM. As an interface between the atmospheric and hydrological components, Noah LSM provides HMS with the precipitation  $P$ , potential evaporation  $E_p$  (evaporation from water bodies), local surface runoff  $R$  and water amount percolated into the bottom soil layer  $S_{inf}$ . Since the time interval of Noah LSM is 30 minutes while that of HMS is 1 day, the Noah LSM outputs ( $P$ ,  $E_p$ ,  $R$  and  $S_{inf}$ ) at the 30-min interval are aggregated to 1-day values for HMS.

### STUDY AREA AND DATA SETS

The Chishui River is a tributary of the Yangtze River in China, situated upstream of the Three Gorges Dam region. It has a total watercourse of 523 km and a drainage area of 20 440 km<sup>2</sup>. The annual mean precipitation in this area is around 1070 mm and the annual mean runoff is 498 mm. As shown in Fig. 2, the area controlled by the Chishui streamflow station (16 622 km<sup>2</sup>) was selected as the study area for the simulations. Since the spatial resolution of the grid cells for hydrological simulations was set as 10 × 10 km<sup>2</sup>, all the spatial inputs of Noah LSM-HMS were prepared at this resolution. The data sets used for model simulations are described in the following.

A DEM pre-processing module HYDDEM was used to aggregate the 1-km USGS HYDRO1K (2001) elevation data (Verdin & Verdin, 1999) to the 10-km resolution, and to derive topographical information such as surface elevation, river depth, elevation of water surface, and upstream area at the same resolution.

Hydro-geological data, including thickness of aquifer, soil porosity and saturated hydraulic conductivity were derived from the Chinese Geology Dataset (Scale 1:4 000 000) and aggregated into the 10-km resolution.

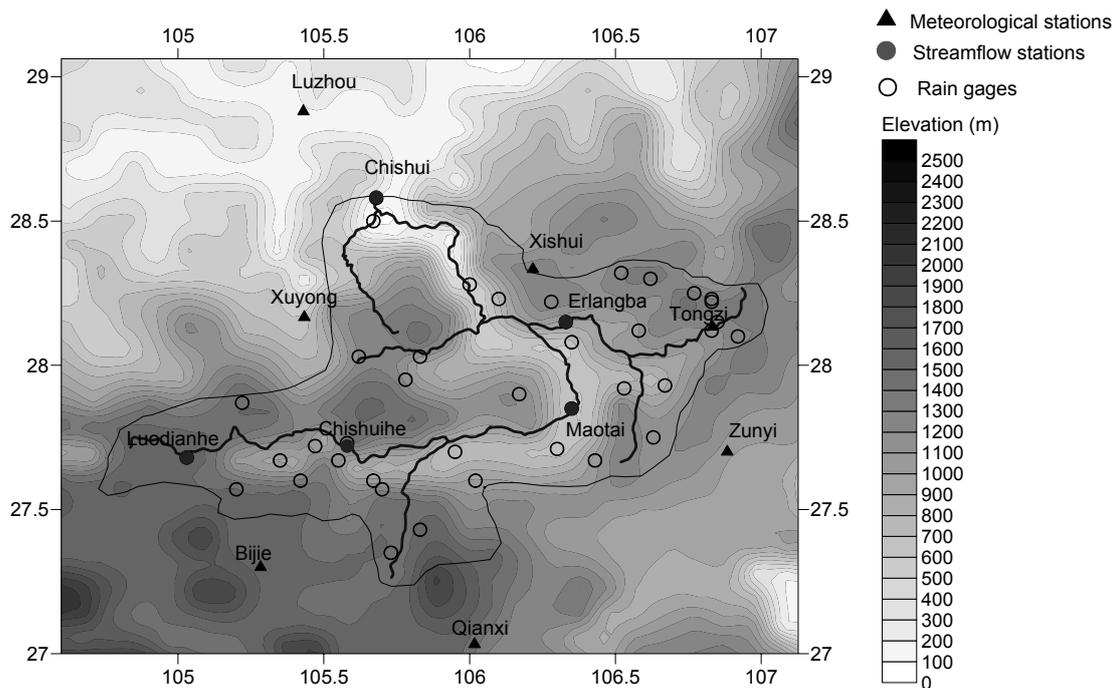


Fig. 2 Geographical information of the Chishui watershed.

The FAO digital soil map of the world was used to represent the soil texture distribution in the Chishui watershed. Soil parameters such as soil porosity, wilting point, saturated soil hydraulic conductivity, matric potential, soil water diffusivity and other related properties for the Noah LSM component were defined according to Mitchell (2005).

The University of Maryland's 1-km global land cover data were adopted to represent the land cover in the watershed. For each land cover type, parameters including green vegetation fraction, canopy albedo, roughness length and minimum stomatal resistance were derived from LDAS (land data assimilation system, <http://ldas.gsfc.nasa.gov/LDAS8th/MAPPED.VEG/LDASmapveg.shtml>).

Noah LSM-HMS requires the following seven basic near-surface atmospheric forcing data at the 30-min time interval for each computational grid cell: air temperature, air relative humidity, surface pressure, wind speed, surface downward long-wave radiation, surface downward solar radiation and precipitation. For these meteorological forcings, spatio-temporal interpolation was conducted to interpolate or convert the routine daily meteorological records at seven meteorological stations and daily precipitation data at 40 rain gauges to each grid cell at the required spatio-temporal resolution (30 s in space, and 30 min in time). To interpolate the precipitation data from daily scale to 30-min time interval, an empirical equation (Kondo & Xu, 1997) was used, based on the statistics of the observed precipitation data at short time intervals at rain gauges in China. A validation study for the precipitation downscaling was not conducted here; to try to reduce the uncertainty from precipitation interpolation, this study will be done in the future.

As shown in Fig. 2, daily streamflow data at five hydrological stations in the Chishui watershed were obtained from the data centre of Hohai University, China. Since the areas controlled by the Luodianhe and Erlangba streamflow stations are relatively smaller, the DEM pre-processing tool HYDDDEM fails to depict their watershed topography correctly. Thus we used only the streamflow data from the Chishui, Maotai and Chishuihe stations in the years 1977–1986, 2001 and 2003–2005 for model calibration and validation.

## NUMERICAL SIMULATIONS AND RESULTS

The coupled Noah LSM-HMS system was run over the Chishui watershed on 10-km grid cells. A complete simulation consists of three individual runs in order to remove the effect of the arbitrary initial conditions of the HMS component on simulation results. To complete one simulation, these three individual runs are conducted in sequence: (1) Cold start mode: in the first phase, a 58-year simulation is done using the full Noah LSM-HMS system, with the arbitrary initial conditions that the groundwater table is at 20 m below the land surface. (2) Spin-up mode of groundwater + vadose zone: in the second step, the groundwater and vadose zone modules in HMS only are driven circularly for 3000 years to allow the groundwater tables to reach, or come close to, equilibrium, using the surface annual mean infiltration from the cold start mode as forcing. (3) Full model mode: with the values of the state variables at the last time step in the groundwater spin-up mode as the initial conditions, the full Noah LSM-HMS model is driven.

In this study, we obtained observed daily routine meteorological data for the years 1977–2005 (29 years in total). In the coupled model system, the time step of the Noah LSM part is 30 min, while that of the HMS part is 1 day. Therefore, all the 29 years of daily meteorological data were interpolated into values at a 30-min time interval and Noah LSM was driven by the 30-min forcing data. Subsequently, the Noah LSM part produces 30-min outputs such as precipitation, potential evaporation, local surface runoff  $R$  and water amount percolated into the bottom soil layer. These Noah LSM outputs were aggregated into daily values as the inputs for HMS. Finally the HMS part gives the daily streamflow results for analysis. To further reduce the effects of the uncertainty of initial conditions on streamflow simulation, the third individual run of Noah LSM-HMS was driven for 58 years, reading the observed meteorological forcing in the years 1977–2005 twice over. The simulation results of the last 29 years in the third individual run were analysed.

In the simulation period (1977–2005), only the daily observed streamflow data at the Chishui streamflow station in the years 1977–1986, 2001 and 2003–2005 were available. In terms of the

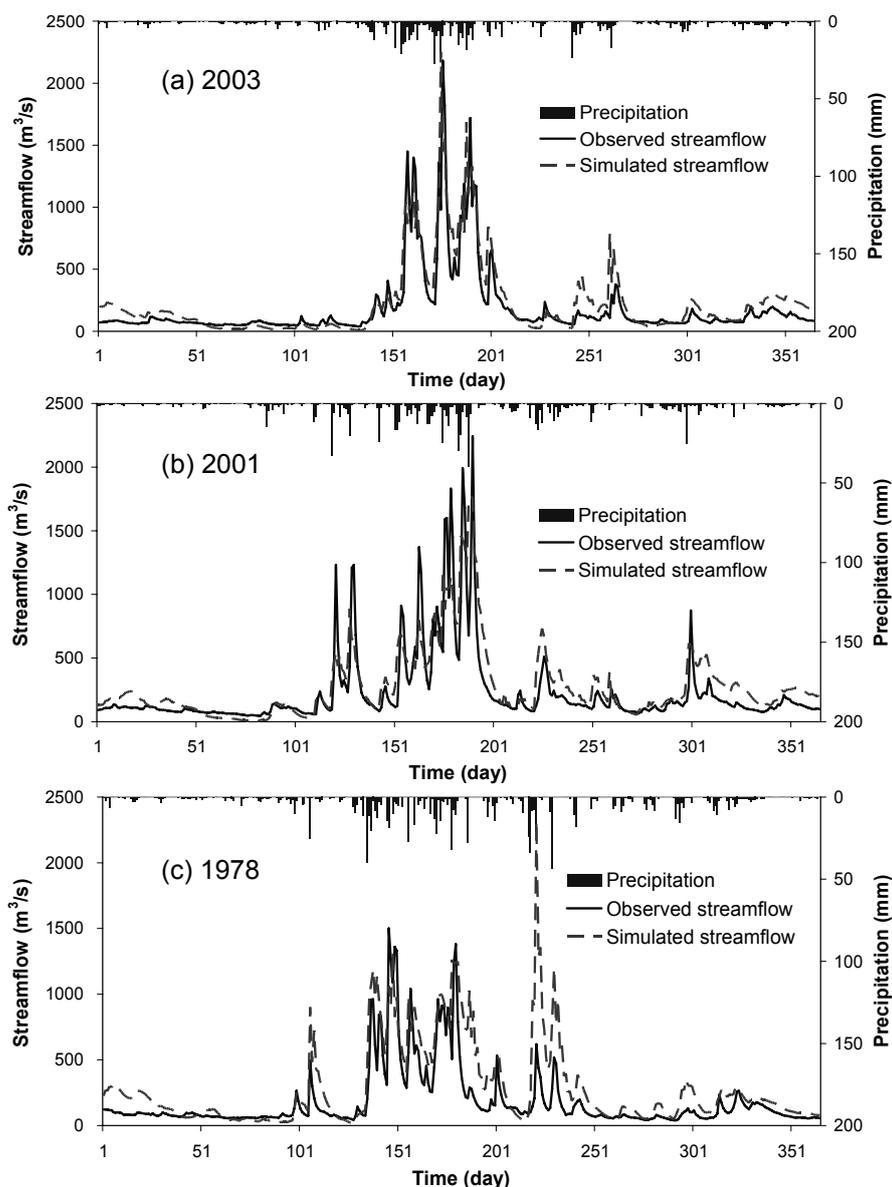
precipitation data, the intensified daily precipitation observations (40 raingauges within the watershed) in the years 2001 and 2003–2005 were obtained, and in other periods (1977–2000 and 2002) the precipitation data recorded at seven meteorological stations near or in the watershed were available. Based on the assumption that the model parameters calibrated with more detailed precipitation data are closer to their actual values, the period of 1 January 2003 to 31 December 2005 was chosen for model calibration. The years 1977–1986 and 2001 were selected as the validation period. Model parameters such as *CZIL* (Zilintikevich parameter) and *REFKDT* (surface runoff parameter) in the Noah LSM part, and *ROUGHDEF* (Manning roughness coefficient) in the HMS component were calibrated by the trial-and-error method. The objective function for model calibration is the commonly-used Nash-Sutcliffe model efficiency coefficient (*Nash*).

Table 1 summarizes the results of Noah LSM-HMS model calibration and validation at the Chishui watershed. In the calibration period (2003–2005), the calculated annual runoff depths are overestimated by >20% and the simulated hydrographs (dashed line in Fig. 3(a)) match the observed (solid line in Fig. 3(a)) quite well, with the Nash-Sutcliffe coefficients being 0.73, 0.56 and 0.83, respectively. Regarding the validation period, the simulated streamflows in the years 1977–1986 and 2001 are compared with the observed values. As shown in Fig. 3(b), the computed hydrograph in 2001 is in fair agreement with the measured (*Nash* = 0.68), except for a minor underestimation of the flood peaks in the middle of the year. As to the simulation in other validation years, their *Nash* values are relatively lower than that in 2001, but acceptable. This difference may result from the precipitation inputs. The simulation in 2001 uses the raingauge-based precipitation data that are derived from more observation sites (40 gauges), while the simulations in the years 1977–1986 adopt the gridded precipitation data set that is interpolated from only seven meteorological stations, of which only two stations are located within the watershed (Fig. 2). Uncertainties in precipitation products are very important. Inadequate or inaccurate precipitation information, to some extent, may influence model simulation. In this study, downscaling the precipitation data from the daily scale to 30-min time resolution may also impact the streamflow simulation. As shown in Fig. 3(c), large error exists between the observed and simulated hydrographs in the validation year 1978. In July and August especially, the simulated streamflow is much higher than the observed. This phenomenon may be attributed to the large error in precipitation inputs. Table 1 shows that the calculated annual runoff depth in each simulation year is higher than the observed. In the validation years (1977–1986), the relative error between the simulated annual runoff depth and the observed is even bigger, over 50% in 1978,

**Table 1** Results of Noah LSM-HMS calibration and validation over the region controlled by the Chishui station.

	Year	<i>P</i> (mm)	<i>Rsim</i> (mm)	<i>Robs</i> (mm)	<i>Error</i> (%)	<i>Nash</i>
Calibration period	2003	753.6	434.0	357.0	21.6	0.73
	2004	920.7	584.0	433.3	34.8	0.56
	2005	838.1	504.1	418.1	20.6	0.67
Validation period	1977	1094	784.3	591.3	32.6	0.60
	1978	981.3	557.0	353.7	57.5	0.16
	1979	1020.1	656.8	472.7	38.9	0.57
	1980	1039.9	737.7	498.0	48.1	0.13
	1981	885.1	560.9	380.6	47.4	0.37
	1982	1098.7	919.2	573.9	60.2	0.24
	1983	1197.0	985.1	609.7	61.6	0.30
	1984	1021.9	791.7	507.4	56.0	0.16
	1985	927.0	669.5	519.3	28.9	0.57
	1986	979.1	744.1	475.4	56.5	0.28
	2001	894.2	535.4	442.1	21.1	0.68

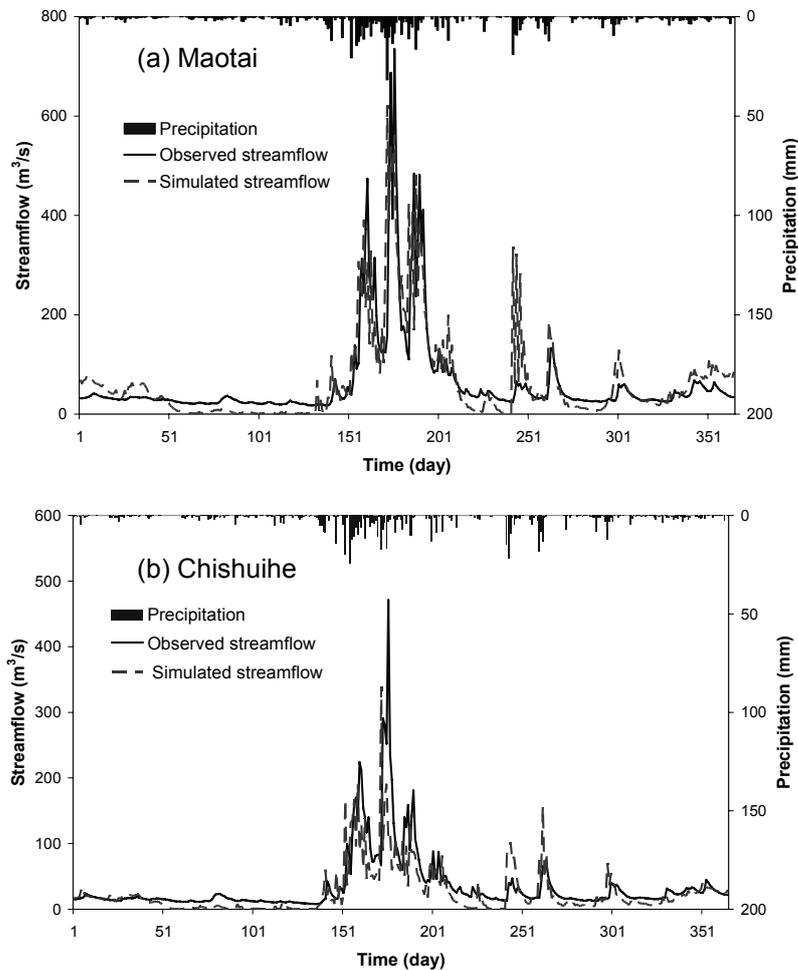
Note: *P* is the annual precipitation, *Rsim* is the simulated annual total runoff depth, *Robs* is the observed annual total runoff depth, *Error* is the relative error between the simulated and observed annual total runoff depths, and *Nash* is the Nash-Sutcliffe model efficiency coefficient.



**Fig. 3** Comparison between the observed and simulated streamflow at the Chishui streamflow station in the years 2003 (a), 2001 (b) and 1979 (c).

1982, 1983, 1984 and 1986. This overestimation of streamflow may be caused by the combination of the errors in Noah LSM, the hydrological model HMS itself, and the input precipitation, but also probably results from human-activity influences in the watershed such as irrigation practices and reservoir operations that tend to reduce some natural flows. Overall, Noah LSM-HMS is able to reproduce streamflow processes at the Chishui hydrological station reasonably well with routine meteorological observations as its input.

Furthermore, streamflow simulations were conducted at the Maotai and Chishuihe streamflow stations, which are located upstream of the Chishui station, and have control areas of 8003 and 3141 km<sup>2</sup>, respectively (see Fig. 1). Figure 4(a) shows that the simulated streamflow at the Maotai station agrees quite well with the observed (*Nash* of 0.61), except for the minor underestimation of low flow in drier seasons. The situation of the streamflow simulation at Chishuihe is a little different. Although Noah LSM-HMS can basically capture the daily variation of streamflow at Chishuihe (Fig. 4(b)), the simulated streamflow on most days within the year is lower than the



**Fig. 4** Comparison between the observed streamflow and the Noah LSM-HMS simulated streamflow at the Maotai (a) and Chishuihe (b) streamflow stations in the year 2003.

observed and the overall annual runoff depth is underestimated by 27.0%. Besides the existing model structure problem, there are two possible reasons for this issue: (1) As shown in Fig. 1, fewer raingauges are located within the Chishuihe region, especially in the area north of the river. Precipitation of the Chishuihe region may also be underestimated and subsequently cause the underestimation in the streamflow. (2) The area controlled by the Chishuihe station is the mountainous headwater region of the Chishui watershed, where the hydro-meteorological conditions are highly spatio-temporally heterogeneous. The input meteorological forcings that are interpolated from a small number of stations may not capture the actual meteorology of the Chishuihe region, and, to some extent, may impact the streamflow simulation.

## CONCLUSIONS

In this study, the Noah LSM-HMS model system that couples the Noah LSM land-surface module of the mesoscale meteorological model WRF with the large-scale hydrological model HMS on 10-km grid cells was developed and applied for simulations over the Chishui watershed within the Yangtze River basin, China. Detailed hydrological processes such as interactions among unsaturated soil water, groundwater, river water and lake water are considered explicitly in Noah LSM-HMS. This method is designed for interactive hydrometeorological simulation driven by a mesoscale meteorological model. The calculated streamflows at the watershed outlet and two

upstream hydrological stations are in reasonable agreement with those observed. Differences between the simulated and observed streamflow still exist. The possible causes are due not only to the probable errors in the structure of the coupled system, but also to errors in the input meteorological forcings, especially precipitation. The simulation over the mountainous headwater region is still not very accurate. It is suspicious that the 10-km resolution may not be fine enough to represent the main hydrological processes in this area. Therefore, it is worthwhile to test the effects of varying grid size of coupled hydro-meteorological models on streamflow simulations. Currently, we only use the meteorological observations to drive Noah LSM-HMS and WRF is not included to perform meteorological simulations in the online mode. In the next step, Noah LSM-HMS will be linked directly to WRF.

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