Prediction of evapotranspiration and streamflow with a distributed model over the large Wuding River basin

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Abstract A GIS-based distributed hydrological model (LISFLOOD) is used to simulate the evapotranspiration and streamflow over the large Wuding River basin of China, with LAI being retrieved from remote sensing NDVI. The model runs over 1995 for calibration and 1996 for validation. It is shown that the model can simulate the rainfall–runoff processes well in the wet season and is poor when simulating the baseflow in winter. The evapotranspiration is the principal component of water budget, the annual amounts of which are different over the land use types. Soil evaporation is greater than transpiration and sensible heat flux is 1.5 times higher than latent heat flux at the basin scale. About 78% of the rainfall amount is infiltrated into soil and 6% for surface runoff. The annual amount of recharge to groundwater is small.

Key words distributed hydrological model; evapotranspiration; streamflow; Wuding River basin

INTRODUCTION

Land-use/cover changes (LUCC), such as desertification, deforestation and reforestation in semiarid and arid regions are significantly altering the hydrological cycle and surface energy balance over a basin. The interactions between topography, vegetation, soil and climate in a basin determine the hydrological regime in a complex way, resulting in strong spatio-temporal variability of hydrological cycling processes. Prediction of the resulting changes on water cycles at the basin scale requires a distributed hydrological model that takes into account the relationships between hydrology, vegetation and atmosphere.

By embedding a soil–vegetation–atmosphere transfer (SVAT) model into a distributed hydrological model, the spatial and temporal variability of the involved processes described by SVAT models can be transferred to basin scales under the support of detailed physical–geographic properties (Strasser & Mauser, 2001; Beven, 2002). Remote sensing information, such as Normalized Difference of Vegetation Index (NDVI) which provides reliable phenological evolution of vegetation greenness over a large area, has been used widely to retrieve biophysical parameters (Maisongrande *et al.*, 1995; Gao, 1995; Sellers *et al.*, 1996) for such models.

The purpose of this study is to simulate the daily evolution of evapotranspiration and streamflow over the Wuding River basin, China, from 1995 to 1996, with a distributed model (LISFLOOD) coupled with a SVAT model. First, the study area and the data are briefly described. Then a section outlining the distributed model follows. Next, it describes how to retrieve vegetation leaf area index (LAI) from NDVI. Finally, simulation results in river discharge, evapotranspiration, surface energy budget, infiltration, surface runoff and recharge are presented.

STUDY AREA AND DATASET

The Wuding River basin, one of the largest sub-basins of the Yellow River, is located in the Loess Plateau of China at the range of 107–111°E and 37–39.5°N, covering an area of 30 261 km^2 (Fig. 1). The altitude ranges from 600 to 1800 m with the main flatland being about 1200 m above sea level in the northwestern part of the basin. The length of the main stream is 491.1 km with a mean slope of 1.97‰. Annual precipitation is about 400 mm, while most of the rainfall events occur in the summer monsoon season, especially from July to August. The yearly mean stream flux is about 30 $m^3 s^{-1}$. Mainly due to human disturbance, the Wuding River basin has been severely threatened by water erosion in summer and wind erosion in winter.

The land-use/cover is classified into six types in the basin, namely, agricultural field, deciduous broadleaf forest, mixture forest, dwarf shrub, grassland and desert with fractions of 22.4%, 1%, 0.3%, 10%, 45% and 21.4%, respectively. The soil texture is distinguished as sandy loam, sandy silt, sand, silt and coarse sand, among which 55% is sandy silt. The basin is divided into 29 370 grids with 1 km resolution. A

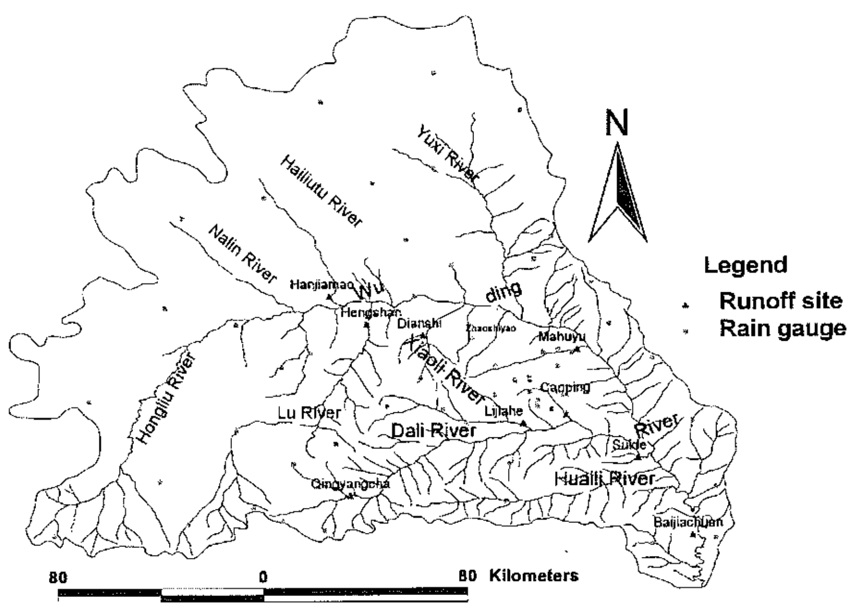

Fig. 1 The channel network of the Wuding River basin.

DEM from US Geological Survey is used to derive the stream channel pattern and the slope of each grid in the basin.

Daily precipitation records at 82 raingauges over the whole basin and meteorological records at 18 climatological stations in and around the basin are available from 1995 and 1996. The precipitation and meteorological measurements are interpolated to each grid with the distance weight least squares method.

MODEL

The distributed hydrological model is mainly based on LISFLOOD designed for large basin water cycle and flood prediction (De Roo *et al.*, 2000). It is a GIS-based model with PCRaster programming. In the model frame, the influences of topography, precipitation, land use and soil types are taken into account. A two-layer canopy energy balance SVAT scheme (Shuttleworth & Wallace, 1985) and the variable infiltration capacity scheme (Liang & Lettenmaier, 1994) describing the subgrid heterogeneity of infiltration are embedded into the original LISFLOOD model (Mo *et al.*, 2002). Both overland and channel runoff are routed with the kinematic wave equations. The model runs over 1995 and 1996 with a 1-km^2 grid size and daily time step.

LEAF AREA INDEX, LAI

LAI is an important biophysical variable that regulates the land surface energy partitioning between canopy and the underneath soil surface, as well as canopy rainfall interception. Uncertainty of LAI may result in bias on evapotranspiration and thus on water balance estimation. Numerical experiments showed that LAI changes of 1 resulted in 5% annual evapotranspiration variation (De Roo *et al.*, 2001).

In this study, monthly maximum composite NOAA–AVHRR NDVI with 1 km resolution in 1996 is utilized to retrieve vegetation canopy LAI. Annual evolution of LAI is interpolated to daily values for simulation purposes. A linear scaling between LAI and NDVI is applied as follows (Chen & Cihlar, 1996):

$$LAI = LAI_{max} \frac{NDVI}{NDVI_{max}} \tag{1}$$

where LAI_{max} is the maximum leaf area index, $NDVI_{max}$ is the maximum vegetation index. The LAI_{max} and $NDVI_{max}$ for the six vegetation types are set as Table 1. In the

Table 1 Ratio to the whole basin area, maximum values of *LAI* and *NDVI*, annual precipitation and evapotranspiration for the land cover types (A: Agricultural fields; B: Deciduous broadleaf forest; C: Mixed forest; D: Dwarf shrub; E: Grassland; F: Desert).

	A	B	C	D	E	F
LAI_{max}	4	5	4	4	4	0
$NDVI_{max}$	0.674	0.721	0.721	0.674	0.674	--
Precipitation (mm)	389	397	326	352	361	312
Evapotranspiration (mm)	400	335	371	333	386	191

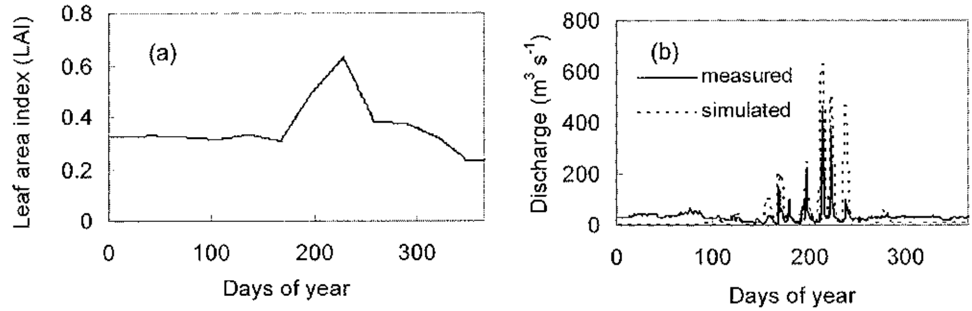

Fig. 2 (a) Daily evolution of the averaged leave area index. (b) Comparison of the simulated and observed daily discharge at the basin outlet.

Wuding River basin, the average LAI is small most of the year and the maximum value of 0.6 occurred in July and August as shown in Fig. 2(a).

RESULTS

River discharge

The model runs over 1995 and 1996 with rainfall and meteorological input at daily time step. The observed discharge at the outlet Baijiachuan in 1995 is used to calibrate the model. The most sensitive parameters to discharge simulation are river channel Manning roughness coefficient N and the infiltration parameter B, which describes the partitioning of rainfall into infiltration and surface runoff. Parameter B is sensitive to total discharge, whereas N is sensitive to the temporal phase of the hydrograph. The two parameters are adjusted manually to calibrate the discharge. On the annual time scale, the difference between the simulated and measured discharge is 5% and the Pearson correlation coefficient of daily discharge is 0.64. The model is able to simulate the rainfall–river flow process well in two of three peaks in summer as shown in Fig. 2(b). Comparing with the basin average rainfall, it is obvious that the simulated discharge highly corresponds to the rainfall processes (Fig. 3). However, since there are some reservoirs and flood-lagging dams in the basin to reduce the flood peaks and discharge volume, considerable differences between the simulated and measured discharges exist as the present model has not taken into account reservoir effects for the streamflow prediction. It is also noticed that the daily average observed discharge is about 30 $m^3 s^{-1}$ in winter, which is much higher than the simulated discharge.

Evapotranspiration

The results in 1996 show that the evapotranspiration amount (342 mm $year^{-1}$), which is very close to the averaged precipitation (356 mm $year^{-1}$), is undoubtedly the principal term of water balance over the Wuding River basin. The residual of precipitation minus evapotranspiration (14 mm) is lower than the simulated runoff depth, which can be explained by the difference compensated from soil moisture and groundwater

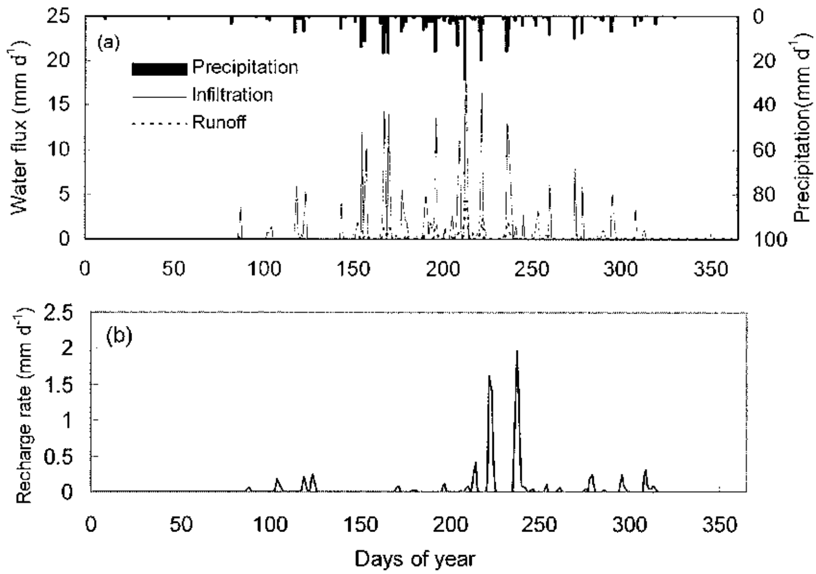

Fig. 3 Daily precipitation, infiltration and surface runoff (a) and recharge rate to groundwater (b) over the basin.

storage. Usually it takes about five years for soil water storage to reach the equilibrium (Strasser & Mauser, 2001).

As shown in Table 1, the yearly value of evapotranspiration from the agricultural field is the greatest, the next being that from the grassland. In the desert, the evapotranspiration is quite small, consuming only 61% of total precipitation. As a consequence, a large amount of soil water is recharged to the groundwater. This may explain why the groundwater level is much shallower in the desert part of the basin. Evapotranspiration from some other vegetation types exceeds the precipitation supplied from soil moisture storage.

As shown in Fig. 4(a), there is no remarkable difference between the annual evolution patterns of transpiration *TR* and soil evaporation *ES*. As expected, the

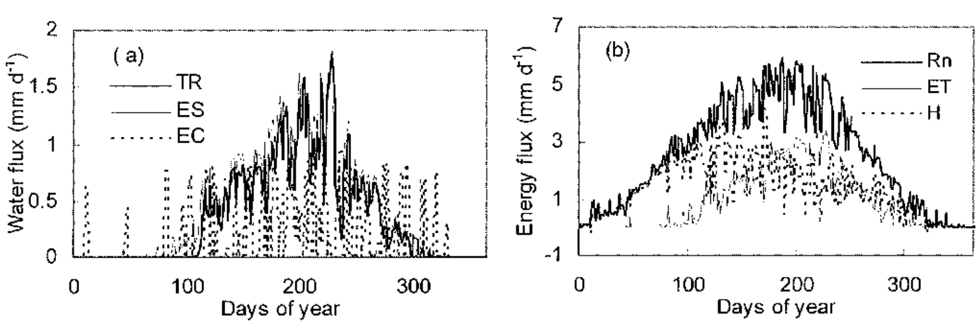

Fig. 4 (a) Daily evolution of transpiration (*TR*), soil evaporation (*ES*) and canopy intercepted water evaporation (*EC*) over the basin. (b) Daily net radiation (*Rn*), latent heat flux (*ET*) and sensible heat fluxes (*H*) over the basin.

evaporation from vegetation canopy intercepted water *EC* only occurred on raining days. Annually, the ratios of *TR*, *ES* and *EC* to *ET* are 0.38, 0.46 and 0.16, respectively, which means that the soil evaporation exceeds transpiration in this arid and semiarid basin. This may be due to the high proportion of desert with a low vegetation cover fraction and LAI.

Surface energy budget

Assuming that soil heat flux is a small term of the surface energy budget on a daily scale, we only concentrate on net radiation *Rn*, latent heat flux *ET* and sensible heat *H* for surface energy budget. It is shown that *ET* (with water depth equivalence in mm) was very small in the early spring and winter period when precipitation was scarce, and then reached its high values stage from Days of Year (DOY) 170 to 230 when the rainy season arrived and the vegetation was well developed (Fig. 4(b)). Annually *Rn*, *ET* and *H* are 914, 337 and 485 mm, respectively, and the Bowen ratio is 1.43, indicating that the sensible heat flux is almost 1.5 times higher than latent heat flux in this basin.

Infiltration, surface runoff and recharge to groundwater

In the Wuding River basin, most of the rainfall that reaches the ground surface is infiltrated into the ground (78%), and only a small part is assigned to surface runoff (6% or 22 mm), as shown in Fig. 3(a). However, there are always two to three heavy storms in summer that may cause considerable flooding and inundation conditions. Since annual precipitation is inadequate in the basin, soil moisture is usually low. As a result, percolation is also small. It is found from daily simulation that the maximum daily recharge is about 2 mm day^{-1} after a heavy rainfall and the yearly recharge amount is about 14 mm (Fig. 3(b)).

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