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A DISTRIBUTED BIOSPHERE HYDROLOGICAL MODEL (DBHM) FOR LARGE RIVER BASIN

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Distributed representation of spatial information and physical description of hydrological processes are necessary in large river basin because of the highly nonlinear hydrological processes and the variability of the spatial heterogeneity. It is important to represent both geomorphologic properties and land cover characteristics in hydrological simulation in large river basin. The DBHM (distributed biosphere hydrological model) employs a flow intervals discretization scheme in the representation of geomorphologic properties and a simple biosphere model in the representation of land cover characteristics to simulate integrate hydrological processes in a large river basin. The geomorphologic properties are abstracted from digit elevation model. The hydrological part estimates the surface runoff and calculates the interlayer exchanges within the soil profile and interaction between soil water and groundwater. The land cover characteristics are described by satellite data and the flux transfer between atmosphere and vegetated surface is calculated by a realistic land surface model SiB2. The DBHM can represent the role of both topography and land cover characteristics in hydrological cycle. The model was applied to the Yellow River Basin to investigate its applicability to a region with large variations in topography, land cover and climate. The hydrological simulation has implemented by hourly time step with a spatial resolution of 10 km mesh. The simulated hydrographs were compared with observations for evaluation of the model performance. The results shows evaporation in irrigation districts is much larger than the evaporation in the surrounding area in semi-arid area, indicating human water regulation had affected the hydrological cycle in the Yellow River basin.

Key Words : *distributed hydrological modeling, biosphere, SiB2, Yellow River*

1. INTRODUCTION

The formation of a distributed biosphere hydrological model (DBHM) for use in large river basin is presented. The model system DBHM is a continuous-time spatially distributed model, integrating hydrological processes and vegetation- atmosphere transfer processes at the river basin scale. DBHM incorporates a previously developed land surface model SiB2 [1)] and a distributed hydrological sub-model, including the use of satellite data to describe vegetation state and phenology and the use of Digital Elevation Model (DEM) data to describe geomorphological characteristics. The principle motivation for formulating DBHM was to provide more realistic estimates of evapotranspiration and runoff over large river basin. The model can be used to investigate runoff change according to land cover change and to assess water resource in large basin.

Hydrological models with a spatial structure are being increasingly based on DEM or Digital Terrain Model (DTM) [2)]. DEMs automatically extract topographic variables, such as basin geometry, stream networks, slope, aspect, flow direction, etc. from raster elevation data. Many of the existing models, such as SHE [3)], TOPMODEL [4)], GBHM [5)6)], etc., use DEMs to represent geographical characteristics of a watershed. The adaptation of DEM improved the representation of runoff accumulation processes. However, the conceptual prescription of land surface and empirical evaporation calculation were recognized weaknesses of most of the distributed hydrological model. Distributed representation of land surface is still a challenge for large scale modeling because of the limitations of global observations. Satellite data gives a chance to describe the vegetation phenology. Vegetation index data acquired from meteorological satellites were processed to derive time series fields of the Fraction of Photosynthetically Active Radiation absorbed by green vegetation canopy (FPAR), the total Leaf Area Index (LAI), and the canopy greenness fraction (N). The remotely sensed data can be integrated into hydrological model and enhance the accuracy of evaporation calculation. Several scientific developments prompted a radical improvement of DBHM. First, meteorologists provided new insights into heat flux in the Soil-Vegetation-Atmosphere Transformation (SVAT) processes [7)8)]. Second, remote sensing became matured as a tool to get reliable land surface information. Third, topographic variables extracted from DEMs provided a plausible way to describe runoff accumulation on ground and in subsurface [9)5)].

The advantages of the DBHM can be summarized as follows:

(i) The calculation of evaporation is more reliable by using a physical land surface scheme for simulation of heat flux in the SVAT processes.

(ii) Satellite data is used to describe time serial land cover change. It becomes possible to estimate hydrological responses in ungauged basin by using satellite data.

(iii) The meteorological observations from hydro-meteorological stations, such as precipitation, temperature, humidity, vapor pressure, sunshine duration, and wind speed, are used in the model. The model could be coupled with atmospheric model by using the outputs from atmospheric models instead of observations.

2. MODELING STRATEGY

The land surface sub-model is based on a biophysical approach to modeling the surface energy and moisture balance, in large part using methodologies developed by micrometeorologist and agricultural scientist [1)10)].

SiB2 of Sellers et al. [1)] was used in the land surface sub-model. In SiB2, satellite data was used to describe the vegetation phenology of a given DBHM grid area. A realistic canopy photosynthesis- conductance model was incorporated to describe the simultaneous transfer of CO_2 and water vapor into and out of the vegetation. The hydrological part of the SiB2 simulated the surface runoff of the given DBHM grid area and calculated the interlayer exchanges within the soil profile and interaction between soil water and groundwater.

The hydrological sub-model is based on geomorphological characteristics of the river basin to modeling the surface and subsurface flow, mainly using DEM-based methodologies developed by hydrologists [11)5)].

The surface runoff flowing to a river system was described by one dimensional kinematic wave model [12)13)]. An approach from Rushton and Tomlinson [14)] was used to estimate groundwater and river water interaction. Realistic watershed map and river way map were used to delineate sub-river basins and river network. The sub-river basins were coded following Pfafstetter method [15)11)]. The runoff was then accumulated and routed to outlet using kinematic wave approach.

The incorporation of land surface model SiB2 with its most critical processes, evapotranspiration, derived from satellite observations and heat flux simulation in the SVAT processes represents the major improvement in DBHM over other distributed hydrological models. Subsequent sections provide the details of the DBHM.

3. THE MODEL STRUCTURE

This section briefly reviews the atmospheric boundary conditions, physical parameters and prognostic variables of land surface sub-model SiB2 and describes the soil layer and groundwater layer interaction, runoff conduction to river network, river basin delineation, river routing and the governing equations of the distributed hydrological sub-model. The overall model structure is shown in Fig. 1.

The atmospheric boundary conditions necessary to force SiB2 include air temperature T_m, vapor pressure e_m, wind speed u_m, precipitation P, shortwave downward radiation $Swdown$, incoming longwave radiation $Zlwd$, and CO_2 and O_2 concentration c_m and o_m at a reference level, z_m, within the atmospheric boundary layer. In practice, mean values of c_m and o_m be defined (35 and 2090 Pa, respectively) for current atmospheric conditions. Daily air temperature, vapor pressure, wind speed and precipitation data from over 8000 worldwide stations was available at Global Surface Summary of Day Data Version 6 (GSSDD; URL: http://www.ncdc.noaa.gov). The station observation data was interpolated to ten kilometers grids for DBHM model. The shortwave downward radiation was estimated from meteorological observations

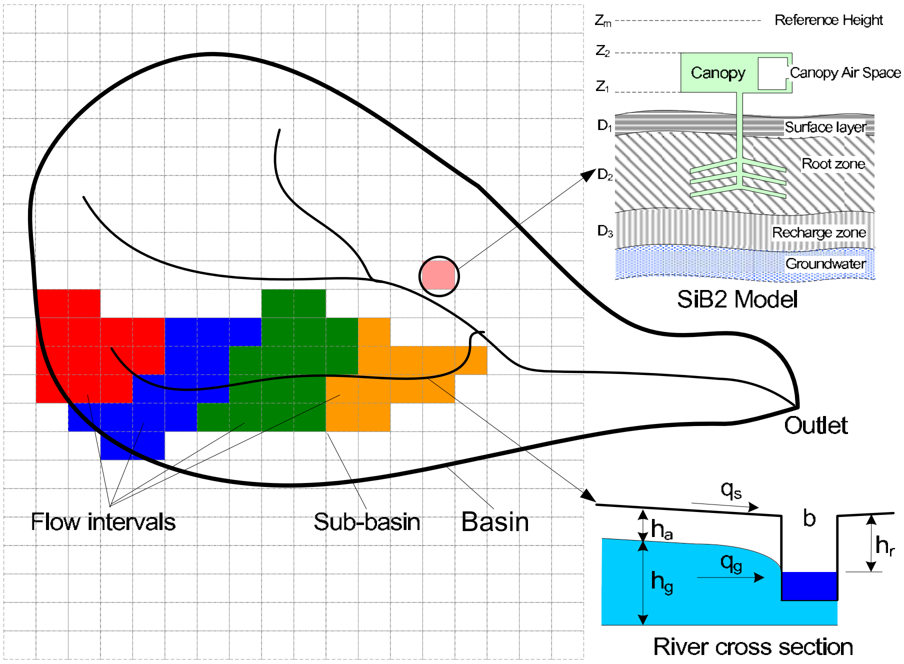

Fig. 1 Structure of the DBHM model.

following Revfeim [16] and Yang [17]. The incoming longwave radiation was estimated as [18)19)]:

$$Zlwd = \varepsilon_a \sigma T_a^4 \tag{1}$$

where ε_a is the atmospheric emissivity, σ is the Stefan-Bolzmann constant, and T_a^4 is the air temperature (K). ε_a is presented as a function of water vapor pressure:

$$\varepsilon_a = 0.66 + 0.039\sqrt{e_a} \tag{2}$$

where e_a is the vapor pressure (kPa).

Time invariant vegetation and ground parameters and time varying vegetation parameters of SiB2 were obtained from satellite data or assigned following Sellers et al. [1]. SiB2 land cover is available at USGS Global Land Cover Characterization data (GLCC; URL:
http://edcwww.cr.usgs.gov/landdaac/glcc/). Global LAI and FPAR based on Pathfinder Version 3 Normalized Difference Vegetation Index (NDVI) with spatial resolution 16 kilometers could be obtained from Myneni et al. [20]. The Food and Agriculture Organization (FAO) global soil type map (Source: Land and Water Development Division, FAO, Rome) was used to produce the DBHM grid soil properties such as soil water potential at saturation Ψ_s(m), soil hydraulic conductivity at saturation K_s (m/s), soil wetness parameter B, porosity θ_s and averaged slope S_s [21]. Soil optical properties are still assigned by vegetation type by SiB2 default.

DBHM have fifteen prognostic physical state variables: twelve variables of land surface sub-model SiB2; three water depth (surface overland flow depth h_s, groundwater depth h_a and river water depth h_r). The surface overland flow is simply described by the one dimensional kinematic wave model including the continuity equation [12)22)]:

$$\frac{\partial h_s}{\partial t} + \frac{\partial q_s}{\partial x} = i \tag{3}$$

and momentum equation:

$$q_s = \frac{1}{n} S_0^{1/2} h_s^{5/3} \tag{4}$$

where q_s is the overland discharge per unit width (m^2/s), t is time (s), x is the distance along the overland flow (m), i is surface runoff in water depth (m), S_0 is the friction slope gradient, and n is Manning's roughness parameter. The flow between the river network and the groundwater is considered to be controlled by the same mechanism as leakage through a semi-impervious stratum in one dimension [14]. This mechanism, based on Darcy's law, where flow is a direct function of the hydraulic conductivity and head difference, can be written as:

$$q_g = \frac{K_s}{h_g}(h_r - h_a) \tag{5}$$

where q_g is the flow between groundwater and river water and h_g is the aquifer thickness. If q_g is positive, it is base flow for gaining streams. Whereas if q_g is negative, it is river recharge for losing streams. The river flow is governed by continuity equation [12),13)]:

$$\frac{Q}{x} + \frac{A_r}{t} = q_s + q_g \tag{6}$$

and momentum equation:

$$Q = \frac{1}{np^{2/3}} S_r^{1/2} A_r^{5/3} \quad (7)$$

where Q is river discharge (m^3/s), p is wetting perimeter (m), S_r is river bed slope and A_r is river cross section area (m^2).

The river basin can be extracted from DEM by using the watershed function of ARC/INFO. If the realistic river way and watershed border are available, they can be used to modify the DEM and help to produce river network and river basin. First, find the grids on the river network according to the realistic river way map. Then "burn into" the river network by changing the elevation value of these grids to some units (e.g. 100 units) less. For all the grids out of the realistic watershed border, modify the elevation value of these grids to some units (e.g. 100 units) larger. The river network produced from the modified DEM will then fit the realistic river way map. For the grids over the watershed border, the area fraction, which means the area fraction inside the realistic watershed, is considered. The modeled river basin area will fit the realistic watershed area.

Identification of sub-river basins is an indispensable step in large river basin modeling to route the river network and support water resource management. The Pfafstetter numbering scheme for delineation and codification of river basin is used which is based on topographic control and the topology of the river network. The system is founded upon concepts first articulated by Pfafstetter [15] and detailed documented by Verdin [11]. The numbering scheme is self-replicating, making it possible to provide identification numbers to the level of the smallest sub-basins extractable from DEM. The routing order of the sub-basins is implicated in the Pfafstetter code. Within a given smallest sub-basin, flow intervals are specified to represent the time lag and accumulating processes in river network according to the distance to outlet of the sub-basin. For each flow interval, a virtual river section is allocated. All the river water recharge in the grids of the flow interval is accumulated to the 'virtual' river section and led to the outlet of the river basin.

4. APPLICATION

The DBHM has been applied to the Yellow River basin to investigate its applicability to a region with large variations in climate and land cover. The simulations were implemented by hourly time step from 1994 to 2000. Basic data representing topography, land cover, soil type were prepared in 10 km mesh grids derived from HYDRO1K (HYDRO1k Database; URL: http://lpdaac.usgs.gov/gtopo30/hydro/), GLCC and FAO, respectively. The river bed slope is derived from DEM data using the average maximum technique [23]. The slope for overland flow is obtained from the FAO soil map. Values Manning's roughness for natural stream range between 0.03 and 0.04. A value of 0.035 is used in this study. The river width is specified along the river network, using the geomorphological relationship between river width and mean annual discharge [24]. The river bed depth from the ground is assigned as the maximum flow depth in the river way. The irrigation water withdrawals are considered according to previous study [25].

The Yellow river is the second-longest river basin in China. It originates from the Tibetan plateau, drains through the northern semiarid region, crosses the loess plateau, passes through the eastern plain, and finally discharges into the Bohai Gulf. The whole basin has an area of 794,712 km^2. The Yellow River basin and river way in China and the river basin and river network derived from ten kilometers DEM are shown in Fig. 2.

The meteorological data was obtained from the China Meteorological Administration (CMA) and GSSDD. Observation data at 287 stations was interpolated to ten kilometers grids with thin plate splines. The simulated hydrographs at 9 locations were compared with the river discharge observations for evaluation of the model in the years when the gauge records were available.

The results show that the model can perform well in the Yellow River basin. Fig. 3 gives the simulated and observed daily hydrographs comparison at an upper stream gauge Tangnaihai station and the river outlet gauge Lijin station. The model can capture the major features of the hydrographs. At river outlet gauge Lijin station, the simulated discharge is larger than the observation in the flood season. The dry-up phenomenon in the low water period is simulated after considering irrigation water withdrawals. The simulated discharge was less 100 m^3/s in 66% of days during the three years period from 1995 to 1997. The discharge records show that the Yellow River stopped

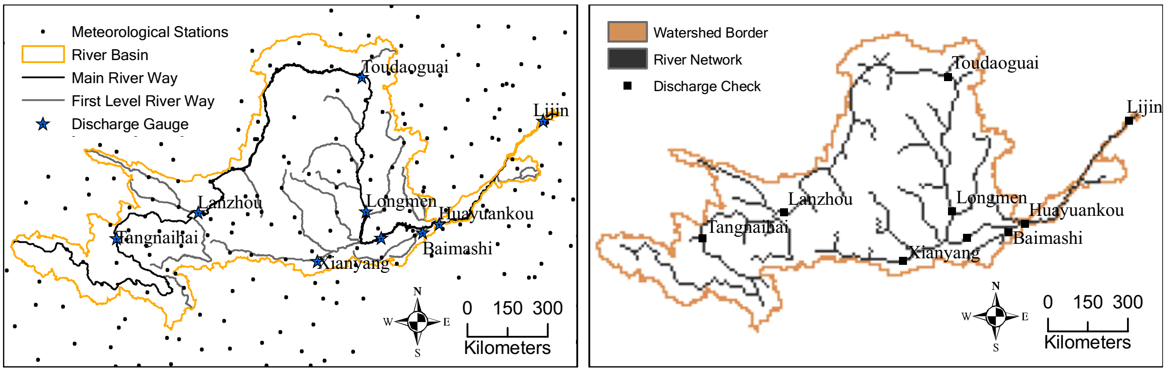

Fig. 2 The Yellow River basin and river way (Left); DEM derived river basin and river network (Right).

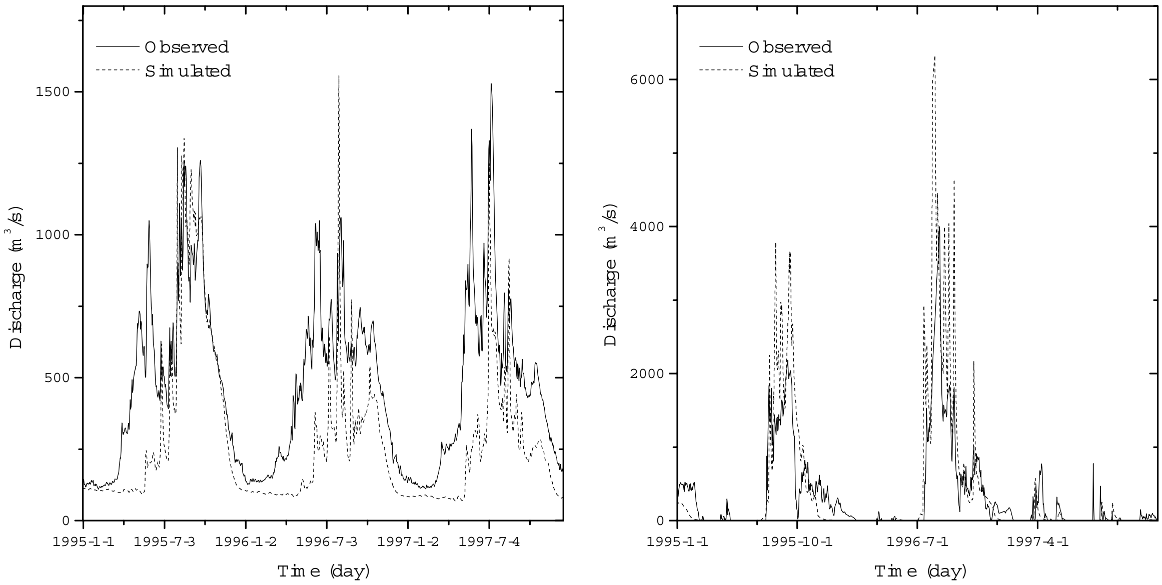

Fig. 3 Comparison of daily hydrographs at Tangnaihai station (Left) and Lijin station (Right).

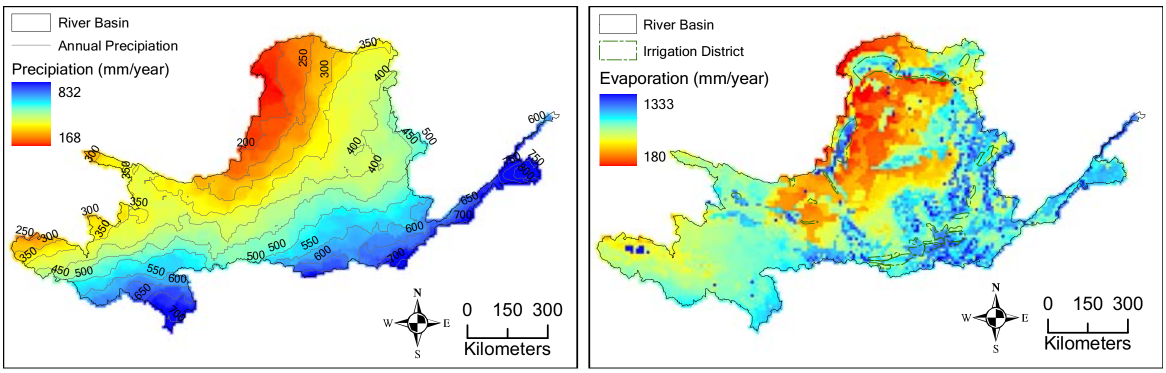

Fig. 4 Spatial distribution of annual precipitation and evaporation in the Yellow River Basin.

flowing for 438 days at Lijin station during the three years period from 1995 to 1997. The observed discharge was less 100 m^3/s in 57% of days during the same time period. A possible reason for the disagreement in hydrograph is artificial water regulation, such as reservoirs and water diversions. According to International Commission on Large Dams [26)], there were 207 reservoirs in the Yellow River basin. The annual precipitation and evaporation is given in Fig. 4. The largest evaporation occurs in the grids where the land use is water surface. The results shows evaporation in irrigation districts is much larger than the evaporation in the surrounding area in semi-arid area. This indicates the artificial water regulation has affected the hydrological cycle in the river basin.

5. CONCLUSIONS

Representation of surface heterogeneity is important in land surface parameterization model. Most of the present land surface models focus on only one side of topography parameterization and SVAT processes. The DBHM can capture the characteristics of the catchment topography properly and also describe the SVAT processes by calculating the transfer of energy, mass and momentum between the atmosphere and the vegetated surface. Application of the DBHM in the Yellow River basin shows it performs well in a region with large variations in climate and land cover. The results indicate the artificial water regulation has affected the hydrological cycle in the river basin. The model could be coupled with atmospheric model by using the outputs from atmospheric models instead of observations.

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