

## **Expanding distributed hydrological modelling to the continental scale**

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**Abstract** Applying a grid-based distributed hydrological model to a continent cannot be achieved simply by increasing the grid size. This is due to the spatial heterogeneity and nonlinear nature of soil–vegetation–atmosphere transfer processes. Sub-grid hydrological parameterization is required to capture the spatial variability in a large grid. The methodology presented in this study expanded a grid-based distributed hydrological model to the continental scale, and addressed both sub-grid hydrological parameterization based geomorphological property and the basin-based flow routing. The spatial information related to topography, land cover, and soil properties was estimated from the available finest resolution data sets. Application to the Asian continent has shown good simulations of river discharge in the main rivers, and the model could represent the general spatial hydrological characteristics. This continental-scale hydrological model can be coupled with GCMs for complete simulation of the continental water–energy cycle.

**Key words** continental scale; hydrological model; GBIM model; sub-grid parameterization; runoff generation; flow routing

## **INTRODUCTION**

Continental-scale hydrological modelling is important for many purposes related to freshwater resources and environments. It is also expected to couple with general circulation models (GCMs) as a useful tool for forecasting the variation of water resources under possible climate changes. One of the main objectives of continental-scale hydrological models is to evaluate the influences of local changes (such as land cover changes) on the whole water cycle (both the vertical fluxes and lateral surface water flow). Therefore, it is necessary to use as much as possible of the spatial information that is available concerning the simulation area and to employ the physically-based descriptions of hydrological processes in the model. Although spatial information is recognized to be important for land surface parameterization in GCMs, just a set of soil and vegetation parameters have been commonly employed in the simulation of vertical flux exchanges between the land surface and the atmosphere (Sellers *et al.*, 1996a). Topographical parameters have been widely used in hydrological models, but they have not been directly employed in the runoff simulations in most GCMs. In addition, it is essential to incorporate an efficient scheme in the GCMs

for appropriate simulation of the function of rivers (Yang *et al.*, 2001). Unfortunately, most existing land surface models focus on the vertical heat flux rather than the horizontal water movement. Although much research has addressed continental/global-scale flow routing using terrestrial models, runoff was taken as input, and most of them were simple routing models that used constant or variable flow velocity (Olivera *et al.*, 2000). Improvement of runoff generation from each grid point and flow routing across grids is indispensable to the real coupled GCM-hydrological simulations in the future.

Based on previous studies (Yang *et al.*, 2000, 2001), this research has expanded a grid-based distributed hydrological model to the continental scale using a physically-based hydrological parameterization in the sub-grid and basin-based kinematic wave flow routing. A geomorphology-based model scheme was employed in the sub-grid hydrological simulation. The Pfafstetter scheme (Verdin & Jenson, 1996) was applied to number the sub-basins and define the flow sequences among these sub-basins. Application to the Asian continent is presented and discussed in the paper.

## METHODOLOGY

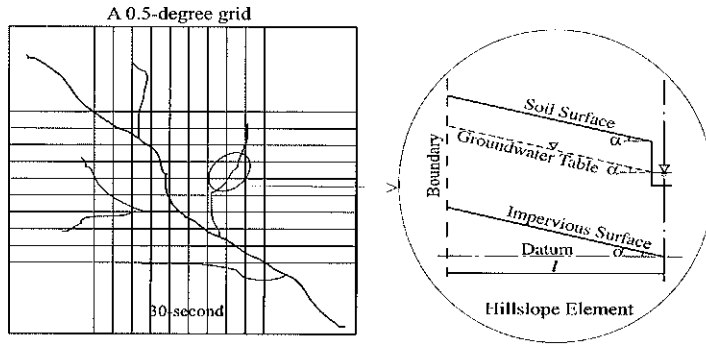
A grid-based distributed hydrological model at the continental scale, using both sub-grid hydrological parameterization and basin-based flow routing, is presented. The model is supported by a number of available global data sets and the GIS commercial software ArcInfo. The topography was simulated using the US Geological Survey (USGS) GTOPO30 data set. The land cover was taken from the USGS 1-km data set of global land cover characterization. The soil properties were obtained from the FAO global soil data set of 5-min resolution. The model uses a grid-system of  $0.5^\circ$  in a geographical projection. Spatial heterogeneity and geomorphological characteristics are considered in the sub-grid hydrological simulations. The river basin boundary and river networks are defined using the  $0.5^\circ$  resolution base map that was derived from the global HYDRO1k data set.

### Sub-grid parameterization

In the geomorphology-based hydrological model (GBHM) developed by Yang *et al.* (2000), the geomorphological properties of river-hillslope formation were used to represent catchment topography (Yang *et al.*, 1998; Herath *et al.*, 1999). In a similar way, it is assumed that a grid is composed of a set of hillslopes located along the rivers. From the macroscale sense, the hillslopes located in a grid are viewed as geometrically similar. The same hillslope model in the GBHM, a rectangular inclined plane with length  $l$  and angle  $\alpha$ , is used. The length is calculated by:

$$l = a(i, j) / 2 \sum L \quad (1)$$

where  $a(i, j)$  is the area of the grid at location  $(i, j)$ ;  $\sum L$  is the total length of streams in the grid, which is calculated using the HYDRO1k data set. Slope angle is taken by the mean slope of all sub-grids in a 1-km DEM. The impermeable bedrock slope is assumed to be parallel to the surface (see Fig. 1).



**Fig. 1** First level sub-grid hydrological parameterization in the continental-scale model.

Land cover categories were resampled from the original USGS 1-km global land cover map, including water bodies, urban areas, bare lands, forests, agricultural uplands, paddy fields, grasslands, wetlands, mixture of grasslands and bare lands, and ice lands, from which the area coverage of each land type in a grid was calculated. The dominant soil types were used to represent the soil properties within a grid. Finally the hillslopes of a grid were grouped into several sets of uniform land-use soil type. The uniform land-use soil hillslope element is the fundamental computational unit for the unsaturated zone water movement. On the hillslope, the unsaturated zone is considered to have a maximum depth of 4 m. Below the unsaturated zone, the minimum unit to represent the unconfined aquifer was the whole volume above the impermeable bedrock over the grid area. This unconfined aquifer volume is a common groundwater storage to all hillslope elements within a grid.

A physically-based model is used to simulate hillslope hydrological response, in which the vertical plane was divided into several layers, including canopy, soil surface, unsaturated zone and groundwater aquifer (Yang *et al.*, 2000). A degree-day model is incorporated to simulate snowmelt.

The canopy interception capacity depends on the vegetation or crop species and differs over time and for vegetation coverage. The actual interception is determined according to the rainfall intensity and deficit of canopy storage (Yang *et al.*, 1998). The actual evapotranspiration is calculated using the potential evaporation that is estimated by Priestley-Taylor's method (Brutsaert, 1982). It is considered individually for each element from canopy water storage, root zone, and soil surface. The actual transpiration from the root zone and evaporation from the soil surface are solved by incorporating into a vertical one-dimensional Richards equation that is employed to describe soil water movement in the unsaturated zone. The surface runoff comprises the infiltration and saturation excesses, which flow through the hillslope into the river and is modelled by the kinematic wave method. The groundwater aquifer is treated as individual storage corresponding to each grid. The exchange between the saturated zone and the river is considered to be steady and calculated using Darcy's law (Yang *et al.*, 1998).

The runoff output from one grid is the sum of hillslope responses (both surface and subsurface runoff) within the same grid. The state variable, soil moisture content, of a grid is the area average soil moisture of hillslopes with different land-use soil types.

The vertical flux, actual evapotranspiration, of a grid is the total evapotranspiration simulated from the hillslopes with different land-use soil types.

### Identification of river basins and flow routing model

For subdividing a continent, the original Pfafstetter basin numbering scheme has been expanded to a continent by Verdin & Jenson (1996). According the continental Pfafstetter system, the largest inland basin is selected and numbered 0, and the four largest basins that directly drain into oceans are selected and numbered 2, 4, 6 and 8 following a clockwise direction. The inter-area between basins 2 and 4 is assigned the number 3. Similarly, inter-area 5 lies between basins 4 and 6, and inter-area 7 lies between basins 6 and 8. The area between basins 2 and 8 is divided into inter-areas 1 and 9. Figure 2 shows the first level subdivision of the Asian continent. The Ob, Yenisey, Lena and Amur river basins have been identified.

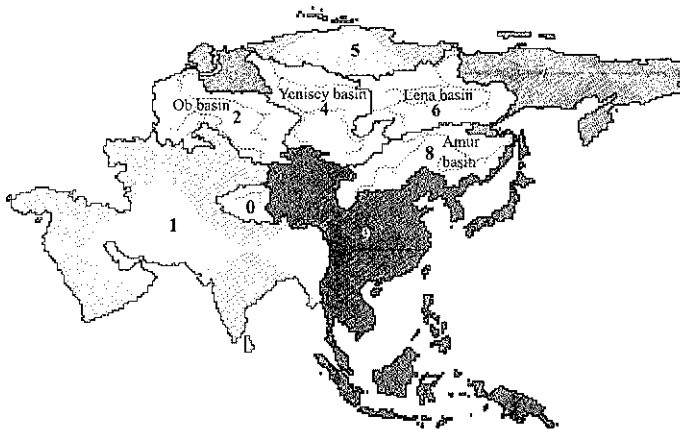


Fig. 2 Subdivision of the Asian continent using the Pfafstetter scheme.

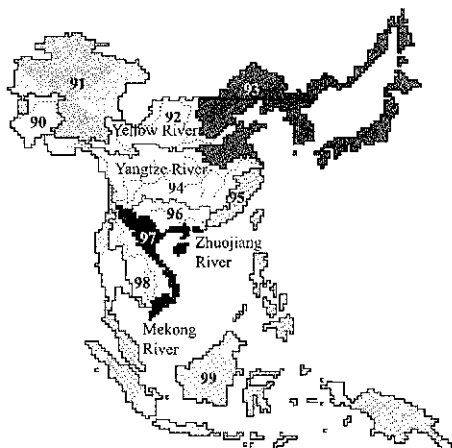


Fig. 3 Second level subdivision of inter-area 9 (Southeast Asia).

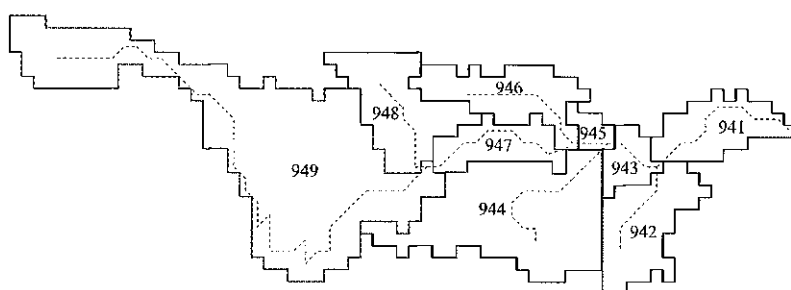


Fig. 4 Third level subdivision of basin 94 (the Yangtze River basin).

Repeating this scheme on the inter-area 9, further divided basins and inter-areas are obtained and coded using two digits, the first digit is the “mother” number and the second digit is its own number (Fig. 3). At the second level, in Fig. 3, the Yellow, Yangtze, Zhuojiang and Mekong river basins have been identified.

This procedure can be repeated on the inter-area until all required basins are identified. Subdividing a basin using the original Pfafstetter basin numbering scheme, first separates the main river and the tributaries. The main river drains a greater area than the tributaries at a junction. Following the main river from the outlet to upper streams, the four largest tributaries are selected and numbered 2, 4, 6 and 8; the interbasins are numbered 1, 3, 5, 7 and 9. Figure 4 shows the subdivision of the Yangtze River basin according to the Pfafstetter system. The sub-basins are numbered using three digits at the third level. This basin numbering scheme can be repeated on any basin or sub-basin until the required accuracy is reached.

Within a derived minimum sub-basin, the river networks are simplified into the main stream on which the simulation of river routing is carried out using the kinematic wave approach. The lateral inflow is the runoff generated from the grids whose locations are given by the flow distances from the outlet. The flow accumulation sequences of the nine sub-basins of the same level is fixed. Sub-basins 9 and 8 join and flow into sub-basin 7; sub-basin 7 and 6 join at their common outlet and flow into sub-basin 5; sub-basins 5 and 4 join their common outlet, then flow into sub-basin 3; sub-basins 3 and 2 join their common outlet, then flow into sub-basin 1. The relationships among the sub-basins are uniquely defined by their code numbers.

## APPLICATION, RESULTS AND DISCUSSION

### Application to the Asian continent

As described above, the Asian continent was subdivided up to the third level to obtain a total of 135 area units, in which 110 basins and 25 inter-areas were obtained (some basins or inter-areas of level 1 and 2 were not subdivided). Twenty discharge gauges (Oki *et al.*, 1999) were registered in the river networks according to their coordinates and drainage areas. A 15-year daily meteorological forcing data set of  $2^{\circ} \times 2^{\circ}$  was estimated from the point observations and stochastic models (Nijssen *et al.*, submitted), which was used in this application. The hydrological simulations have been carried out at a temporal resolution of 1 h. The average snow depth of January

1979 derived from remote sensing (Chang *et al.*, 1992) was used as the initial condition. The maximum values of leaf area index, *LAI*, in a year were used for different vegetation species. The monthly change in patterns of *LAI* in a year were obtained from the *NDVI* of 1987 (Sellers *et al.*, 1996b). A 6-year (1979–1984) simulation was summarized and is presented here.

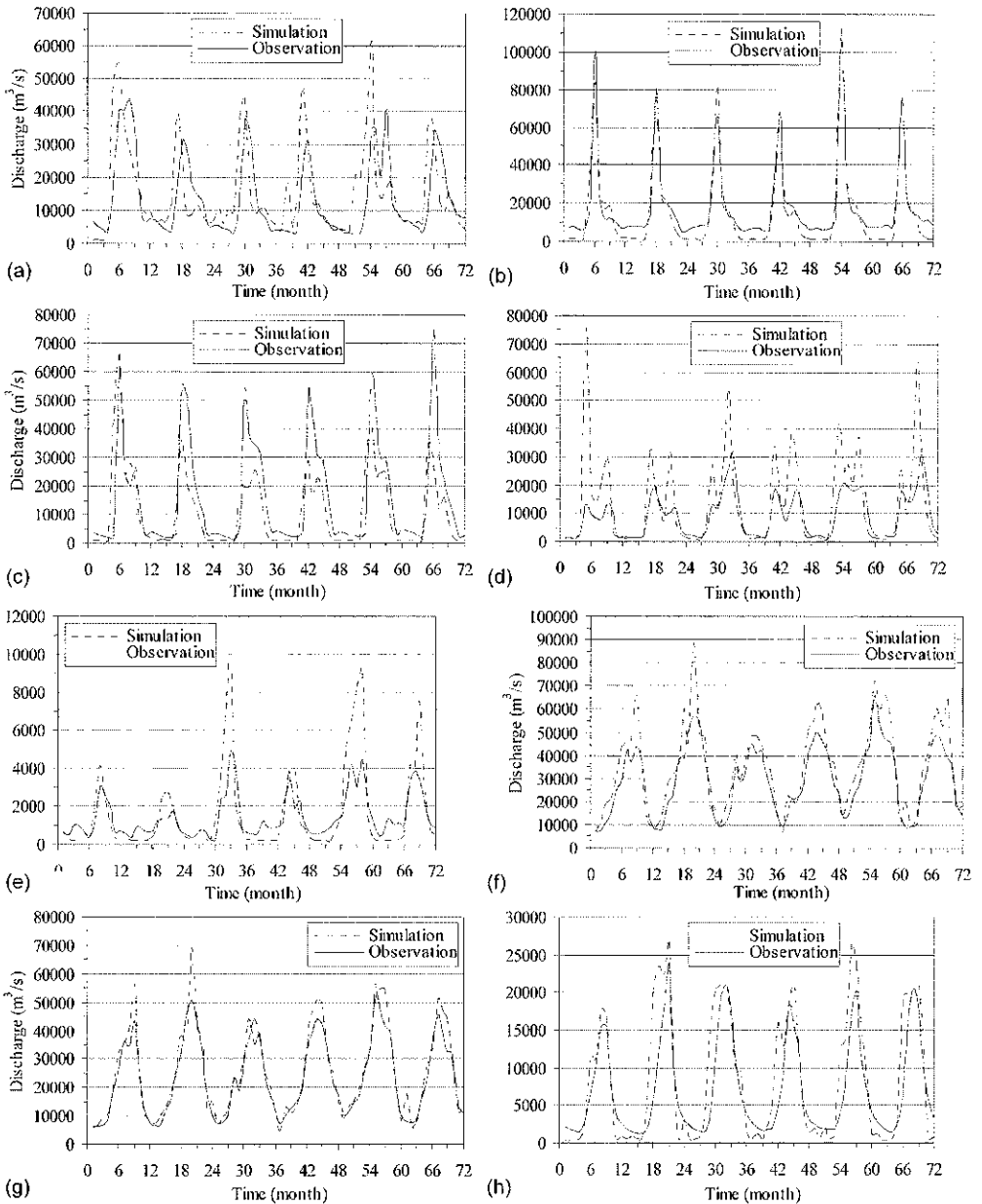
### Annual water balance and river discharge

The basin-based annual water balance values were checked in the nine largest river basins in the Asian continent, namely the Ob, Yenisey, Lena, Amur, Yellow, Yangtze, Mekong, Ganges and Indus. Table 1 shows the results for 6-year simulations from 1979 to 1984. For the entire Asian continent, the annual precipitation was 710 mm, actual evapotranspiration was 343 mm, and the runoff was 374 mm; evaporation and runoff share the precipitation almost equally. In the Ob, Yenisey and Amur basins, evaporation takes about 70% of precipitation. About 85% of precipitation in the Yellow River basin and the Indus basin becomes evapotranspiration. A high runoff ratio has been found in the Yangtze, Mekong and Ganges basins, ranging from 50 to 65%. The annual runoff errors have been calculated for the drainage areas above the gauges in each basin. It was expressed by the ratio of the difference between simulated and observed annual runoff to the observed annual runoff. This error ranges from –13 to 46%. In most cases, the absolute error is less than 20%.

The comparison between simulated and observed monthly hydrographs at eight gauges is shown in Fig. 5 (a)–(h). In general, there is better agreement between the simulated and observed streamflow in temperate and tropical regions than in cold regions. This can be explained by the temperature-based snowmelt model underpredicting the energy flux. This is expected to be improved by including an energy flux

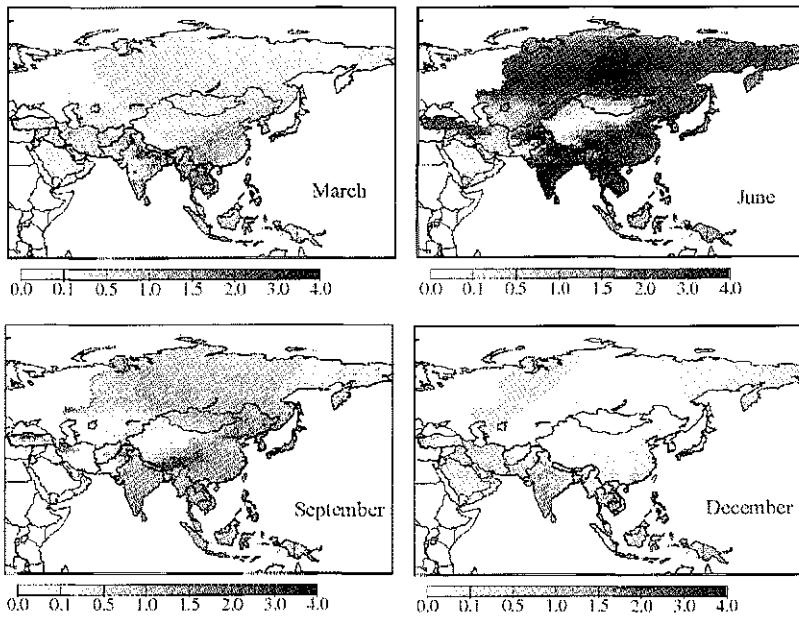
**Table 1** Mean annual water balance of nine main river basins.

Basin/gauge	Entire basin/area:			Runoff error above gauge point (%)
	Precipitation (mm)	Evapotranspiration (mm)	Runoff (mm)	
Ob River (Salekhard)	576	385	180	13
Yenisey River (Igarka)	507	334	186	–13
Lena River (Kusur)	421	317	142	–29
Amur River (Komsomolsk)	469	339	147	46
Yellow River (Huayuankou)	451	379	77	16
Yangtze River (Datong)	1083	456	628	19
Mekong River (Mukdahan)	1625	557	1065	20
Ganges River	1068	532	528	No observed data
Indus River	491	422	76	No observed data
Whole Asian continent	710	343	374	No observed data



**Fig. 5** Comparison between simulated and observed monthly hydrographs: (a) Ob River (Salekhard); (b) Yenisey River (Igarka); (c) Lena River (Kusur); (d) Amur River (Komsomok); (e) Yellow River (Huayankou); (f) Yangtze River (Datong); (g) Yangtze River (Hankou); and (h) Mekong River (Mukdahan).

component in the hydrological model in addition to the movement of water. In the Ob and Mekong rivers, the time lag of the observed hydrograph compared with the simulated hydrograph, could be caused by artificial water controls, such as irrigation and reservoirs. The same reasoning applies to the higher simulated than observed peaks in



**Fig. 6** Seasonal changes of actual evapotranspiration ( $\text{mm day}^{-1}$ ) simulated by the continental-scale hydrological model.

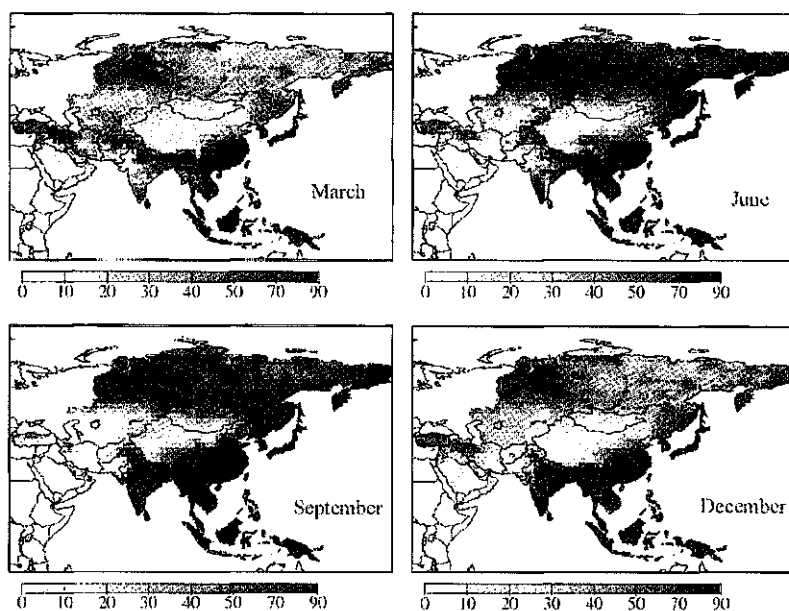
the Amur and Yellow rivers. Not only are the peaks of hydrographs lower, the water balance could be greatly changed by artificial water uses, especially agricultural irrigation. It was reported that nearly 70% of river flow was used for irrigation in the Yellow River basin and this concentrated on several large irrigation areas. The effects of these kinds of artificial water uses should be included in future hydrological modelling to understand both water resources and climate.

### **Spatial hydrological characteristics in the Asian continent**

Hydrological models should have the capability to properly represent spatial hydrological characteristics, especially evaporation and soil moisture. In the present simulation, hourly evaporation can be an output from the model and the soil moisture content is updated using an hourly time step. To show the seasonal changes of evaporation and soil moisture contents, the monthly average values of evaporation and first layer soil moisture were calculated. Figure 6 gives the seasonal changes of actual evapotranspiration and Fig. 7 shows the seasonal changes in soil moisture of the first layer. It was found that the hydrological simulations reflected the general spatial patterns.

### **CONCLUSION**

A continental-scale distributed hydrological model has been developed using a  $0.5^\circ$  grid size in geographical projection for future coupling with GCMs. It employed the geomorphological properties of river–hillslope formation for sub-grid topographical



**Fig. 7** Seasonal changes of soil moisture of the top soil (saturation, %) simulated by the continental-scale hydrological model.

parameterization. A grid was represented by a number of topographically similar hillslopes, and the hillslopes were grouped into several uniform land-use soil types considering the sub-grid spatial variations of land cover and soil properties. The uniform land-use soil hillslope element was the fundamental computational unit for hydrological simulation. A basin-based kinematic flow routing model was incorporated in the hydrological modelling, which employed the Pfafstetter scheme to subdivide the continent and identify the flow sequences among the sub-basins. Application to the Asian continent showed good simulations of river discharge in the main rivers and reasonable seasonal changes and spatial distributions of actual evapotranspiration and soil moisture contents.

This continental-scale hydrological model has the characteristics of (a) comprehensive sub-grid hydrological parameterization based on high resolution global data; (b) river basin-based kinematic flow routing by an efficient scheme; (c) easy coupling with atmospheric models since it uses a grid system based on a geographical projection.

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