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The Xinanjiang model from the perspective of PUB

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Abstract The progress of the Xinanjiang model, a semi-distributed conceptual hydrological model for use in humid or semi-humid regions, including model inputs, model structure and its parameters, is reported from the perspective of the PUB science and implementation plan. Based upon the knowledge that the use of an inadequate model structure may be more problematic than the use of sub-optimal parameter values, the focus of this paper is on the modification of the structure of the Xinanjiang model by considering the relations between sensitive model parameters and catchment characteristics. In particular, the focus is on the biological (mainly referring to vegetation) aspects in order to improve the estimation of evapotranspiration using the energy conservation principle. The upstream catchment of Hanzhong hydrological station in the Hanjiang River, the source region of the middle route of the greater South-to-North Water Transfer Project in China, was selected as the study area. The results shows that the modified version, called the Xinanjiang vegetation-hydrology model, provided similar streamflow simulation results in the calibration period (1980–1983) in terms of the Nash-Sutcliffe model efficiency coefficient, and gave slightly better streamflow simulation results in the validation period (1984–1986).

Key words Xinanjiang model; model structure; leaf area index; digital elevation model; runoff generation; discharge hydrograph; predictions in ungauged basins

INTRODUCTION

A general hydrological forecasting system contains three components: (a) a model that describes the key processes of interest, (b) a set of parameters that represent those landscape properties that govern critical processes, and (c) appropriate meteorological inputs (where needed) that drive the basin response (Sivapalan *et al.*, 2003). Model inputs are of great importance because their distributions both in space and in time make a notable impact on computed results. Model inputs rank first in reducing hydrological uncertainty in the context of PUB (Predictions in Ungauged Basins). Novel data can be obtained from space-borne, air-borne and on-ground measurement, as well as from general circulation models. A well-defined model structure plays a more significant role in a hydrological forecasting system than sub-optimal parameter values. The magnitude of a model parameter within a poor model structure would make less sense, even if calibrated by very advanced optimization methods (Ren *et al.*, 2006). The problem of how much runoff is to be generated from precipitation is more significant than how the runoff is to be routed. Based upon the knowledge that the use of an inadequate model structure may be more problematic than the use of sub-optimal parameter values, the focus of this paper will be on the improvement of the structure of the Xinanjiang model (Zhao & Liu, 1995) by considering the vegetation aspect.

Land surface characteristics are closely related to hydrological processes. In this paper, the Xinanjiang model is modified by considering the relation amongst sensitive parameters and catchment characteristics, particularly biological (mainly referring to vegetation) aspects, for improved estimation of evapotranspiration using the energy conservation principle. This modified version is called the Xinanjiang vegetation-hydrology model. The model structure, data preparation, parameter estimation and application of the Xinanjiang model considering vegetation are described.

MODEL STRUCTURE

The Xinanjiang model has four main characteristics in its structure and related parameters: (a) to compute runoff depth over spatially partitioned units in the horizontal direction, subwatersheds or grids; (b) to estimate evapotranspiration using a three-layer method in the vertical direction; (c) to separate runoff components into surface, subsurface and groundwater flows according to flow velocity; and (d) to conveniently transfer initial values and partial model parameters across temporal scales by means of relations between those parameters on different time scales. For instance, hourly outflow coefficients of the free-water storage to groundwater and subsurface flow are derived from daily estimates because daily hydrological data are more readily available than hourly data in the real situation.

Evapotranspiration Compared with the original Xinanjiang model, the Xinanjiang vegetation-hydrology model employs the two-source evapotranspiration scheme based on the energy conservation principle and resistance network (Mo *et al.*, 2004) to calculate the canopy transpiration of the dry vegetation canopy (E_c), evaporation of the intercepted water on the wet vegetation canopy (E_i) and soil evaporation (E_s) for various vegetation types:

$$E_c = \frac{\varDelta R_{nc} + \frac{\rho C_p D_0}{r_{ac}}}{\lambda[\varDelta + \gamma(1 + \frac{r_c}{r_{ac}})]}(1 - W_{fr}) \tag{1}$$

$$E_i = \frac{\varDelta R_{nc} + \frac{\rho C_p D_0}{r_{ac}}}{\lambda(\varDelta + \gamma)} W_{fr} \tag{2}$$

$$E_s = \frac{\varDelta(R_{ns} - G) + \frac{\rho C_p D_0}{r_{as}}}{\lambda[\varDelta + \gamma(1 + \frac{r_s}{r_{as}})]} \tag{3}$$

where R_{nc} and R_{ns} are the net radiations absorbed by canopy and soil (W m^{-2}) respectively, G is the substrate soil heat flux (W m^{-2}), $\varDelta$ is the slope of the saturation vapour pressure curve (kPa °C^{-1}), ρ is the mean air density (kg m^{-3}), C_p is the air specific heat (KJ kg^{-1} °C^{-1}), γ is the psychrometric constant (kPa °C^{-1}), λ is the latent heat of vaporization (MJ kg^{-1}), W_{fr} is the wetted fraction of the canopy, r_c and r_s are the bulk stomatal resistance and surface resistance of soil, respectively (in s m^{-1}), r_{ac} and r_{as} are the bulk boundary layer resistance of canopy and aerodynamic resistance between soil surface and canopy (s m^{-1}) respectively, and D_0 is the water vapour deficit at the source height (kPa).

Runoff computation Similar to the original Xinanjiang model, three kinds of spatially heterogeneous distributions are used: (a) an uneven distribution of tension water storage capacity throughout the subcatchment or grid cell is expressed by a parabolic curve for partial-area runoff generation; (b) a non-uniform distribution of free-water storage capacity over partial areas where runoff has been produced is also expressed in terms of a parabolic curve for separation of runoff into surface flow, interflow and groundwater flow; and (c) the amount of free-water storage is represented by a linear reservoir structure to account for the different velocities of different runoff components (Ren & Yuan, 2006).

Following Ren *et al.* (2004), the Xinanjiang vegetation-hydrology model assumes that the free water storage capacity (*SM*) is proportional to the vegetation root depth and effective soil porosity. *SM* for each grid cell can be estimated as:

$$SM = SM_{ref} \times D_{root} \times \frac{\phi}{\phi_{ref}} \tag{4}$$

where SM_{ref} is the reference free water storage capacity when the vegetation root depth is 1 m and soil effective porosity is 0.5 m^3 m^{-3} (SM_{ref} needs to be calibrated); D_{root} is the root depth of vegetation in the study grid cell (m); ϕ is the effective soil porosity in the study grid cell (m^3 m^{-3}); ϕ_{ref} is the reference effective soil porosity (m^3 m^{-3}).

Furthermore, the Xinanjiang vegetation-hydrology model calculates the outflow coefficients of interflow and groundwater flow (*KI* and *KG*) based on soil texture. According to the approach adopted in the BTOPMC model (Block-wise use of TOPMODEL and Muskingum-Cunge method; Takeuchi *et al.*, 1999), *KI* and *KG* can be estimated by the equations as follows:

$$KI = KI_{clay} \times U_{clay} + KI_{sand} \times U_{sand} + KI_{silt} \times U_{silt} \tag{5}$$

$$KG = KG_{clay} \times U_{clay} + KG_{sand} \times U_{sand} + KG_{silt} \times U_{silt} \tag{6}$$

where U_{clay}, U_{sand} and U_{silt} are ratios of clay, sand and silt grains (%), respectively; KI_{clay}, KI_{sand} and KI_{silt} are the outflow coefficients of interflow for clay, sand and silt grains, respectively; KG_{clay}, KG_{sand} and KG_{silt} are the outflow coefficients of groundwater flow for clay, sand and silt grains, respectively.

Overland flow and streamflow routing The Xinanjiang vegetation-hydrology model differs from the original Xinanjiang model by using the kinematic wave method to describe the effect of vegetation on overland flow movement. The Manning roughness coefficient for various vegetation types is assigned according to the research work of Vieux (2001). The Muskingum-Cunge method is used for streamflow routing.

DATA AND PARAMETER ESTIMATION

The upstream catchment of the Hanjiang River, which is gauged by the Hanzhong hydrological station, was selected as the study area. The Hanjiang River is the longest tributary in the middle reach of the Yangtze River. This area is located in the source region of the middle route of the greater South-to-North Water Transfer Project in China. The Hanzhong station is located at the outlet of the catchment which has a contributing area of 9349 km^2. The climate is humid with a mean annual precipitation of 900 mm.

Topographic data A digital elevation model (DEM) was obtained from the National Geophysical Data Center, USA, viz. Global Land One-kilometre Base Elevation (GLOBE) data with a spatial resolution of 30 × 30 arc seconds. As shown in Fig. 1(a), the elevation within the watershed ranges from 459 m at the outlet to 3408 m a.m.s.l. at the top of the watershed divide. The digital elevation drainage network model (DEDNM; Martz & Garbrecht, 1992) was used to delineate watershed divides and determine grid-based flow vectors and other attributes.

Land cover The land cover in the Hanzhong watershed was derived from the University of Maryland's 1-km global land cover data (UMD). The UMD data have 14 land-cover classes at a spatial resolution of 30 × 30 arc seconds. As shown in Fig. 1(b), there are seven vegetation types within the Hanzhong watershed, namely deciduous needleleaf forest, deciduous broadleaf forest, mixed forest, woodland, wooded grassland, grassland and cropland, accounting for 17.3, 12.4, 35.1, 16.2, 8.8, 1.7 and 8.5 percent of the total area, respectively. For each type of vegetation, model parameters such as the minimum stomatal resistance, canopy albedo, monthly roughness length, monthly zero-plane displacement, vegetation height and maximum leaf width are derived based on the vegetation information from the land data assimilation system (LDAS http://ldas.gsfc.nasa.gov/LDAS8th/MAPPED.VEG/LDASmapveg.shtml). Vegetation parameters used in this study for different vegetation classes are listed as in Table 1.

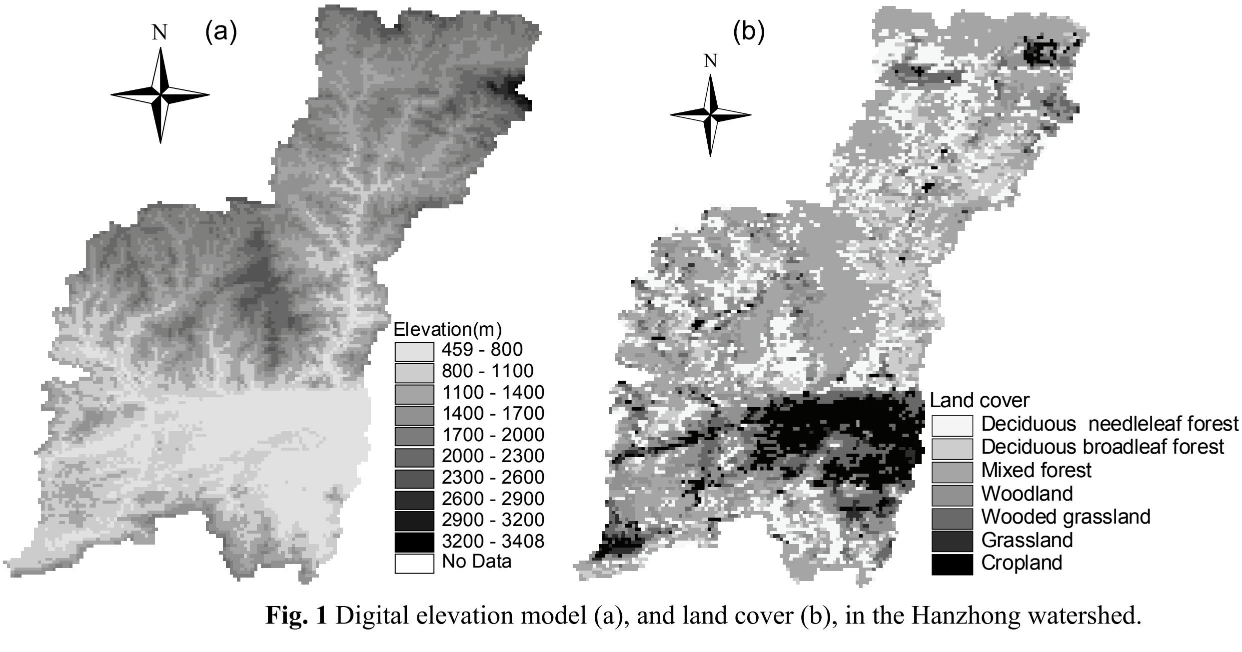


Fig. 1 Digital elevation model (a), and land cover (b), in the Hanzhong watershed.

Table 1 Vegetation-related parameters in the Hanzhong watershed.

Vegetation classification	z_0 (m)	D_0 (m)	$r_{s\min}$ (s m^{-1})	a_c	H (m)	$w_{\max}$ (m)
Deciduous needleleaf forest	1.068–1.112	13.760–13.930	150	0.15	17.00	0.0010
Deciduous broadleaf forest	0.520–1.044	13.660–16.660	150	0.18	20.00	0.0800
Mixed forest	0.812–1.059	13.710–15.258	150	0.17	18.50	0.0400
Woodland	0.755–0.851	10.760–11.498	147	0.20	14.02	0.0195
Wooded grassland	0.349–0.426	4.99–5.558	138	0.23	6.89	0.0187
Grassland	0.076–0.078	0.218–0.325	130	0.23	0.60	0.0100
Crop land (corn)	0.076–0.078	0.218–0.325	109	0.20	0.60	0.0100

z_0: monthly roughness length; d_0: monthly zero-plane displacement; $r_{s\min}$: minimum stomatal resistance; a_c: canopy albedo; h: vegetation height; $w_{\max}$: maximum leaf width.

Leaf area index Leaf area index (LAI) is an important parameter for evapotranspiration estimation which can be retrieved form the normalized difference vegetation index (NDVI). In this study, monthly maximum composite 1-km resolution NDVI data from the National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR) in 1992, 1993 and 1995 were used to calculate the monthly spatial distribution of LAI using the method proposed by Sellers *et al.* (1996):

$$FPAR = FPAR_{\min} + (FPAR_{\min} - FPAR_{\min})\frac{(SR - SR_{\min})}{(SR_{\max} - SR_{\min})} \tag{7}$$

$$LAI = (1 - F_{cl})LAI_{\max}\frac{\ln(1 - FPAR)}{\ln(1 - FPAR_{\max})} + F_{cl}LAI_{\max}\frac{FPAR}{FPAR_{\max}} \tag{8}$$

where SR is the simple ratio ($SR = (1 + NDVI) / (1 - NDVI)$), $FPAR$ is the fraction of photosynthetically active radiation, F_{cl} is the fraction of clumped vegetation, $SR_{\min}$ and $SR_{\max}$ are SRs representing 5% and 98% NDVI populations, $FPAR_{\max}$ and $FPAR_{\min}$ are taken as 0.950 and 0.001, respectively, and $LAI_{\max}$ is the maximum LAI representing fully developed vegetation.

Soil texture The digital soil map of the world developed by the Food and Agriculture Organization (FAO) is used to represent the soil texture classification in the study area. For each type of soil texture classification, information such as the ratios of clay, sand and silt grains are provided by Yamanashi University for model application (Table 2).

Table 2 Soil grain proportions for each FAO soil texture classification in the Hanzhong watershed.

FAO soil number	Ratio of clay (%)	Ratio of sand (%)	Ratio of silt (%)
3963	25.25	45.02	29.73
4350	23.33	55.53	21.14
4365	26.23	52.63	21.15
4405	24.41	57.00	18.59

Meteorological and hydrological data Meteorological data from 1980 to 1986 were obtained from China Meteorological Administration. Data from four meteorological stations (Hanzhong, Lueyang, Ankang, Daxian) were used, including daily readings of mean, maximum and minimum temperatures, sunshine hours and wind speed, and six-hourly records of air water vapour pressure. Moreover, daily precipitation data from 50 raingauges were used. The point meteorological data have to be interpolated over the whole watershed considering the effect of terrain.

Furthermore, observed daily streamflow data at seven streamflow stations (Hanzhong, Yuandun, Tiesuoguan, Chadianzi, Wuhouzhen, Jiangkou and Madao) from 1980–1986 are used for model application.

NUMERICAL SIMULATION

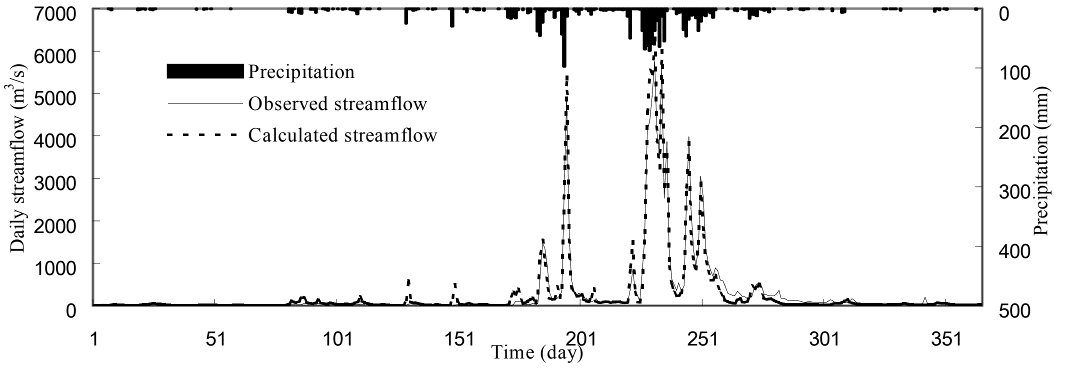
The entire Hanzhong watershed is subdivided into 13 031 grid cells with a spatial resolution of 30 s. The Xinanjiang vegetation-hydrology model is then used to compute the daily runoff in each grid cell, and the simulated runoff on each grid was routed to the outlet at the Hanzhong hydrological station using the Muskingum-Cunge method (Cunge, 1969).

The Xinanjiang vegetation-hydrology model has three types of parameters (vegetation, soil and hydrological parameters). While the vegetation and soil parameters can be derived from vegetation and soil information as described above, the hydrological parameters have to be determined by model calibration. In this study, the daily streamflow records in the period of 1980–1983 were used for model calibration while data from 1984–1986 were used for model validation. For model calibration, the Nash-Sutcliffe goodness-of-fit criterion (Nash & Sutcliffe, 1970) was selected as the objective function.

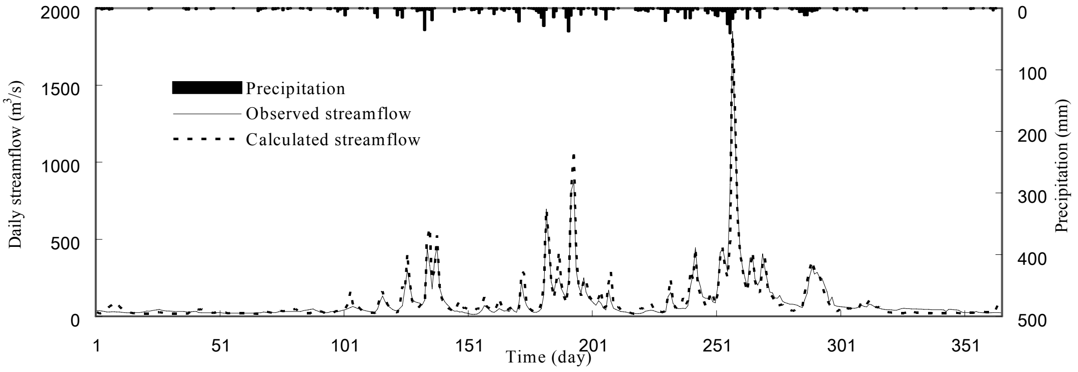
RESULTS AND DISCUSSION

Figure 2 shows the observed and simulated daily streamflows at the Hanzhong station in 1981 (calibration year) and 1985 (validation year). Table 3 shows the comparison of the results of daily streamflow simulation using the Xinanjiang vegetation-hydrology model and the Xinanjiang model respectively. As indicated in Table 3, the Xinanjiang vegetation-hydrology model can reproduce the daily streamflow in the calibration period quite well. All Nash-Sutcliffe coefficients are higher than 0.80, and the relative errors of annual runoff depth are within the range of ±20%. In the validation period, the Xinanjiang vegetation-hydrology model simulates the daily streamflow for the years 1984 and 1985 accurately, but fails to simulate the daily streamflow processes in 1986 satisfactorily with the Nash-Sutcliffe coefficient being lower than 0.80. This phenomenon can be attributed to the fact that 1986 was relatively dry (annual precipitation 703 mm) and prone to human activities, which actually disturbed the natural hydrological processes.

As shown in Table 3, the Xinanjiang vegetation-hydrology model produces a higher Nash-Sutcliffe coefficient when simulating the daily streamflow in 1985 than the Xinanjiang model does. Both models generate similar Nash-Sutcliffe coefficients



(a) 1981



(b) 1985

Fig. 2 Observed and simulated daily streamflows at the Hanzhong station in 1981 (calibration year) and 1985 (validation year).

Table 3 Comparison of the results of daily streamflow simulation using the Xinanjiang vegetation-hydrology model and the Xinanjiang hydrological model.

	The Xinanjiang model considering vegetation		The Xinanjiang model	
Year	Nash-Sutcliffe coefficient	Relative error of runoff depth (%)	Nash-Sutcliffe coefficient	Relative error of runoff depth (%)
Calibration period				
1980	0.800	−16.2	0.890	−17.2
1981	0.959	3.1	0.966	5.1
1982	0.847	13.7	0.918	8.2
1983	0.874	−1.6	0.863	1.8
Validation period				
1984	0.817	4.3	0.873	10.2
1985	0.933	14.7	0.852	8.2
1986	0.768	10.8	0.743	10.6

for the years 1981, 1983 and 1986; however, for the years 1980, 1982 and 1984, the Nash-Sutcliffe coefficients of the Xinanjiang vegetation-hydrology model are 0.090, 0.071 and 0.056 lower than those of the Xinanjiang model. The probable reasons for the errors are as follows:

1. Uncertainty of model parameters. The Xinanjiang vegetation-hydrology model has many more parameters than the Xinanjiang model. Although the main vegetation and soil parameters in the Xinanjiang vegetation-hydrology model are represented using vegetation-specific parameters from the literature, these parameters may not be suitable for application in the Hanzhong watershed and could be responsible for a large degree of model parameter uncertainty.
2. In terms of the notable diurnal variation of solar radiation and evapotranspiration, the Xinanjiang vegetation-hydrology model uses empirical equations to interpolate the daily precipitation data into hourly values, then carries out hourly evapotranspiration and runoff calculations, and finally sums up to provide daily streamflow time series. Because of the importance of accurate precipitation inputs for hydrological modelling, the methodology for downscaling of the precipitation may have a great impact on the daily streamflow simulation. In the future, more reasonable interpolation methods for precipitation should be studied and included in the Xinanjiang vegetation-hydrology model.

CONCLUSION

In this paper, the Xinanjiang hydrological model structure is modified by including representation of catchment vegetation characteristics to improve the estimation of evapotranspiration using the energy conservation principle. Compared to the original Xinanjiang model, the new Xinanjiang vegetation-hydrology model introduces a more detailed physical description of the eco-hydrological processes. It should be noted that increasing the complexity in the model structure does provide additional tuning parameters, but to some extent, produces a few uncertainties in model parameterization. In the future, a quantification of the sensitivity and uncertainty associated with model parameterization by the Monte Carlo method (Beven, 2002) will be carried out, and more useful data sources such as remotely-sensed data and observed soil moisture data will be used for model calibration to constrain the parameters and reduce the prediction uncertainty.

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