MACROSCALE HYDROLOGICAL MODELING OVER THE HUAIHE RIVER BASIN*

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ABSTRACT

The Xin'anjiang Model is used as the basic model to develop a monthly grid-based macroscale hydrological model for the assessment of the effects of climate change on water resources. The monthly discharge from 1953 through 1985 in the Huaihe River Basin is simulated. The sensitivity analysis on runoff is made under assumed climatic scenarios. There is a good agreement between the observed and simulated runoff. Due to the increase of time interval and decrease of precipitation intensity on monthly time scale, there is no monthly runoff in some model girds as the monthly hydrological model is applied to the Huaihe River Basin. Two methods of downscaling monthly precipitation to daily resolution are validated by running the Xin'anjiang model with monthly data at a daily time step, and the model outputs are more realistic than the monthly hydrological model. The methods of downscaling of monthly precipitation to daily resolution may provide an idea in solving the problem of the shortage of daily data. In the research of the climate change on water resources, the daily hydrological model can be used instead of the monthly one.

Key words macroscale hydrological model, Xin'anjiang model, Huaihe River Basin, downscale

I. INTRODUCTION

The study of macroscale hydrological modeling has been inspired by two requirements. One is to improve the capability of prediction for climate change and its effects on water resources and water related aspects; the other is to improve the understanding of hydrologic processes in global water and energy cycle. The increased concentration of greenhouse gases is expected to alter the radiative balance of atmosphere, causing increases in temperature and changes in precipitation patterns and other climatic variables (Houghton et al. 1990). It is very important for water resource managers to be aware of and prepared to deal with the effects of climate change on streamflow and related

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variables. Many studies have shown that land surface processes play an important role within the climate system (Wood 1991; Lin et al. 1996). As a significant component of land surface processes, hydrological processes interact strongly with the climate, i. e. being subject to the climate change as well as feeding back to the climate. The coupling of hydrological model with the atmospheric model would improve the model performance in the simulation and prediction by more accurate description of land surface processes.

Traditionally, hydrological models are categorized into the statistical, physical, and conceptual models. The physical model focuses on describing the physical processes, but limited in practical use due to the shortage of detailed data. While the conceptual model may have a more empirical approach based on variable parameters with only limited relationships between model parameters and conditions in the basin. Hence, the conceptual model is more appropriate for applications at larger scales (Becker 1992). Currently, numerous conceptual hydrological models based on water balance have been developed for the simulation of streamflow patterns over large basins for resource estimation purposes, e.g., HBV model (Vehvilainen and Huutunen 1997), SLURP model (Kite 1997), Macro-PDM model (Arnell 1999). The VIC model has been developed in a series of articles (Wood et al. 1992; Liang et al. 1994; Liang and Xie 2001). The initial motivation for the development of the model was to improve the representation of land surface processes within atmospheric models, more recently this model has been used to simulate continental-scale river basin dynamics (Abdulla et al. 1996; Nijssen et al. 1997).

The Xin'anjiang Model (Zhao 1992) has been proven to be an effective conceptual model, which is developed on the basis of numerous practical work of storm-flood forecasting. It considers the non-uniformity of distribution of rainfall and underlying conditions, with some features of distributed model. The Xin'anjiang Model provides a parameterization scheme for lumping, which recently is considered as a simple and effective spatial parameterization method for use in the macroscale hydrological modeling (Wood et al. 1992; Todini and Dumenil 1992).

In this article, the Xin'anjiang Model is used as the basic model to develop a grid-based macroscale hydrological model for the purpose of exploring the sensitivity of water resources to climate change. The watershed chosen for analysis is the Huaihe River Basin in China. In Section II, we discuss some issues related to the grid-based hydrological model. Then we describe some applications of the Xin'anjiang monthly-distributed hydrological model in the Huaihe River Basin. Due to the increase of time interval and decrease of precipitation intensity within a month, no monthly runoff in some gridded cells appears for the Xin'anjiang monthly model applied to the Huaihe River Basin. In Section III, we present the results for the Xin'anjiang Model with a daily time step with monthly data. Two methods of downscaling of precipitation from monthly to daily resolution are considered and the model results are compared. Finally, we give some conclusions and discussions for the model.

II. GRID-BASED HYDROLOGICAL MODEL

1. *Precipitation Interpolation*

The Xin'anjiang Model is used as the basic model to develop the grid-based distributed hydrological model. The model structure may be regarded as being independent of the size and shape of computational units, and can be directly applied to the grid-based computation. The value of precipitation in each grid cell can be interpolated by the following methods.

• Minimum distance method, i.e. the value observed at the nearest raingauge station is taken as the mean value of a grid.

• Linear interpolation weighted by the distance between a raingauge station and a grid cell to be studied.

As for evaporation, the minimum distance method is used for interpolation in this paper.

2. *Parameter Estimation in the Grid Cell*

Model calibration is very important for a distributed hydrologic model. Usually the parameters of a hydrological model are calibrated through measured data. The accuracy of the model calibration is dependent on errors in observations. The model could be over-parameterized during the model calibration to fit the simulated results to observed data (Yu and Schwartz 1999). There is a high degree of uncertainties in estimating the average values of various hydrologic parameters for each grid cell (Yu et al. 1999). On the other hand, the case without gauged data must be involved in macroscale hydrological modelling. Therefore, an attempt should be made to establish the quantitative relationship between the parameters and land surface characteristics, and to seek for the geographical distribution of the parameters.

Tension water capacity (hereafter WM), is a parameter controlling runoff generation in the Xin'anjiang Model. It is one of the most sensitive parameters in the monthly and daily model, and plays a control role in the estimation of generated runoff and actual evapotranspiration. A good relationship between WM and the drought index (γ) exists, which is defined as the ratio of the annual mean potential evaporation to the annual mean precipitation, which can be quantitatively expressed as

$$WM = C \times \gamma, \quad (1)$$

where C is a coefficient. The analysis of the observed data has shown that the value of C is taken as about 160 mm in the Huaihe River Basin.

All the other parameters in the Xin'anjiang Model have their own physical meanings, and may be estimated on the basis of physiographical characteristics with the development of information technology.

3. *Evaporation Estimation*

Potential evaporation could not be measured. The traditional method to solve the problem in the hydrological model is by means of the conversion of pan-based observation data. The values of the potential evaporation are mainly dominated by the climatic conditions, such as temperature and moisture, which vary with elevation and latitude. However there are no pan-based evaporation data when studying the effects of future climate change on water resources. Thus an evaporation estimation model should be built instead of pan-based data for the Xin'anjiang grid-based hydrological model. A feasible way is to make use of meteorological elements, such as precipitation, air temperature, wind velocity, air pressure, radiation, etc., which could be predicted by GCM (General Circulation Model).

There are various kinds of empirical and physical models to estimate the potential evaporation. An empirical model is easily used but short of physical mechanism, however a physical model is usually applied only to the small scale of pilot area because of the lack of observational data. In this study, the empirical approach is adopted for its simplicity, and the fundamental factor determining the potential evaporation is the energy that comes from solar radiation. Generally speaking, the monthly mean evaporation is proportional to the monthly mean air temperature. Therefore, temperature is considered as the main factor in the establishment of empirical evaporation formula. In the study of monthly hydrological model, a potential evaporation formula is established, i. e.

$$E = A_1 \times T + B_1, \tag{2}$$

where E is monthly potential evaporation; T refers to monthly mean air temperature; A_1 and B_1 are coefficients respectively.

III. APPLICATION OF THE XIN' ANJIANG MONTHLY HYDROLOGICAL MODEL

Monthly hydrological model is considered to be a useful and indispensable tool in assessing the effect of climate change on water resources over a large geographic domain (e. g., Gleick 1986; Arnell 1992; Mohseni and Stefan 1998). In this study, the Xin'anjiang monthly hydrological model (Liu 1993) is used as the basic model to develop a grid-based hydrological model. The Huaihe River Basin with the area of 270 000 km^2 is selected as the research area. A 30 km$\times$30 km squared-grid is adopted and combined with drainage network. There are totally 341 grid cells. The inputs to the model are P, the measured monthly mean rainfall depth on sub-basins, and E, the measured evaporation in the same time step. The outputs are the monthly discharge from each sub-basin and from the whole basin, and the actual evapotranspiration from the whole basin. The state variables are the tension water storage, the free water storage, and generated runoff. The data series for calibration and validation comprise 33-year (1953 — 1985) monthly hydrological data from the whole Huaihe River Basin, including observed precipitation, air temperature, and streamflow. These three types of data come from 210 precipitation stations, 29 evaporation stations, and 36 streamflow control stations, respectively.

For the validation of the grid-based monthly hydrological model, the Huaihe River Basin is divided into 17 sub-areas, in which 15 sub-areas have monthly-observed discharge data. With regard to the two ungauged sub-areas, the model parameters are transplanted from the gauged sub-areas. The model is run in two different situations respectively, i. e.,

A. Calibrated parameters are directly used in grid-based hydrological model, and the values observed by evaporation pan are taken as potential evaporation;

B. Tension Water Capacity, WM, is estimated from Formula (1), and potential evaporation is estimated from Formula (2).

The model results in the two situations are shown in Table1, and we can find that the model efficiency is greatly improved when temperature is used to estimate evaporation. The monthly hydrological model performs good model efficiency with 11 over 0.75 out of 15 sub-catchments. The reasons that the model efficiency of the other catchments is correspondingly lower may be related with the representation of inputs and human activities.

Table 1. Annual Runoff Results from the Monthly Grid-Based Hydrological Model (unit: mm)

Sub-area number	Control station	Observed discharge	A		B	
			Calculated	Efficiency	Calculated	Efficiency
1	Xixian	382.5	382.47	0.868	382.54	0.8768
2	Bantai	219.59	249.67	0.8198	249.71	0.8504
3	Luohe	212.38	211.04	0.8045	212.69	0.8515
4	Zhoukou	148.69	148.96	0.814	148.84	0.8680
5	Boxian	87.72	87.88	0.4197	87.17	0.6653
6	Jiangjiaji	386.93	386.35	0.7896	386.97	0.8438
7	Hengpaitou	791.81	791.41	0.6071	791.64	0.6632
8	Fuyang	159.53	159.89	0.7828	159	0.8525
9	Wangjiaba	300.1	300.63	0.7813	300.01	0.8007
10	Lutaizi	251.71	254.85	0.7496	251.24	0.7621
11	Bengbu	238.01	237.65	0.6361	238.09	0.6504
12	Minguang	175.07	179.3	0.493	182.74	0.6016
13	Guzhen	115.96	115.38	0.7162	115.73	0.7758
14	Linyi	233.57	232.2	0.8347	233.68	0.8471
15	Daguanzhang	243.93	231.22	0.7487	243.75	0.7894
16	Hongze Lake	0	214.87	0	220.91	0
17	Plain area	0	196.23	0	158.24	0
Average				0.724		0.780

The observed and simulated average monthly discharges in years from 1953 to 1985 at Lutaizi with the control area of 91620 km^2 are shown in Fig. 1, and we can find that there is a good agreement between the observed and simulated values.

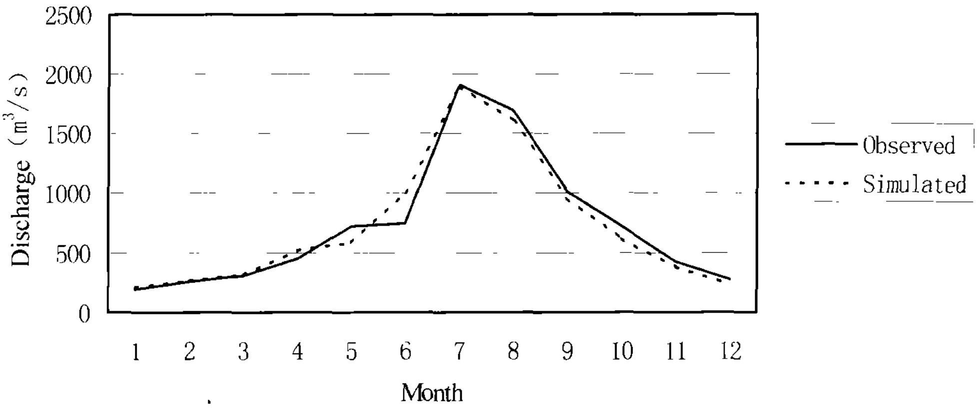

Fig. 1. Observed and simulated average monthly discharges in years from 1953 to 1985 at Lutaizi with the control area of 91620 km^2.

IV. APPLICATION OF PRECIPITATION DOWNSCALING METHODS

1. *Problems in the Xin'anjiang Monthly Hydrological Model*

In Sections II and III. the Xin'anjiang Model was used as the basic model to develop a monthly grid-based macroscale hydrological model. The monthly discharge of the 17 sub-basins in the Huaihe River Basin from 1953 through 1985 was simulated. Though most of the simulated results agree well with the observed data. some problems exist in the monthly hydrological model. such as the runoff production. which may be ascribed to the monthly time step for the model integration.

According to the assumptions in the Xin'anjiang Model. runoff generates only when $P-E>0$. where P is precipitation and E is potential evaporation. For example. there is a month with only one rainy day with the rainfall magnitude of 50 mm, and the monthly potential evaporation is 300 mm: then the daily average potential evaporation is 10 mm. When the model is run at daily time step, the effective rainfall is 40 mm ($50-10=40>0$). then the runoff can be generated. But if the model is run at monthly time step. then $P-E=50-300<0$. and there will be no simulated runoff. which is obviously unrealistic. This indicates that the increasing of the time step may reduce the accuracy of the representation of the daily processes. which will lead to the unrealistic zero runoff in some model grid cells when the monthly hydrological model is applied to the Huaihe River Basin. Figure 2 shows the gridded precipitation in the Huaihe River Basin in October 1953. and Fig. 3 the gridded runoff simulated by the monthly hydrological model at the same time. We can find that there is no runoff in the most grid cells for the model simulation even precipitation exists.

The better way to solve the above problem is to run the model at a daily time step

																			23											
																		82	62	80	73									
												17	21	25	32	32	72	54	73	73	75									
											17	17	23	25	32	44	72	60	51	55	75	79	79							
										22	22	23	23	35	32	44	44	45	44	54	79	79	79							
									23	32	22	24	35	35	44	41	41	41	43	43	42	97								
				24	19	14	13	30	23	23	32	24	24	25	35	30	38	41	39	35	42	97	97	72						
		15	27	27	13	18	14	14	23	23	26	24	25	25	28	30	30	44	32	32	54	97	34	72	34	41				
	16	19	12	17	17	17	14	13	28	30	26	24	25	25	28	28	49	34	27	24	54	37	34	28	41	41				
14	14	27	8	8	18	13	12	13	28	30	28	35	39	39	31	28	28	20	24	24	46	37	37	28	60	60	60			
14	27	24	11	13	13	11	11	27	24	21	26	28	28	29	25	33	22	23	41	41	46	21	29	20	55	58	26			
			23	23	32	11	9	9	27	19	19	33	29	37	42	27	27	23	21	21	21	29	29	29	55	26	26	26		
				23	28	12	26	21	15	26	19	33	28	45	45	27	28	17	19	19	19	29	33	30	39	22	26	41		
				17	17	17	23	21	20	19	44	25	25	45	27	28	28	14	21	19	28	28	18	30	30	30	38	41	41	66
				29	20	15	3	3	19	19	44	41	30	29	28	43	34	34	17	21	28	28	28	43	26	38	38	41	66	66
				29	24	14	14	14	22	21	40	45	32	29	38	43	19	18	17											
					28	20	16	39	21	32	53	53	32	29	49	32	32													
						16	16	39	51	74	59	82	82	78	49															
								51	60	82	82	82	81	78																
											82	81	108	117																
													108	117																

Fig. 2. Distribution of precipitation (mm) in the Huaihe River Basin in October 1953.

																			0											
																		5	0	1	2									
												0	0	0	0	0	0	0	2	3	2									
											0	0	0	0	0	0	2	0	0	0	2	0	0							
										0	0	0	0	0	0	0	0	0	0	0	4	0	0							
									0	0	0	0	0	0	0	0	0	0	0	0	0	1								
				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0						
		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0				
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											
					0	0	0	0	0	0	0	0	0	0	0	0	0													
						0	0	0	0	0	0	0	0	0	0															
								0	0	0	0	0	16	5																
											0	13	43	51																
													43	51																

Fig. 3. Distribution of the simulated runoff by the monthly hydrological model in the Huaihe River Basin in October 1953.

with daily input. Unfortunately, in most cases, only monthly-observed average data are available, and this may suggest the need of the downscaling of monthly data to daily time scale. In this study, the Xin'anjiang Model is run at daily time step with monthly data.

and the model output is with monthly resolution, and two methods of downscaling of monthly precipitation to daily resolution are considered and the model results will be compared.

2. *Data and Methods*

The monthly precipitation data for 33 years (1953—1985) from 210 rainfall stations, and daily precipitation data for 6 years (1980—1985) from 430 rainfall stations upstream of Bengbu in the Huaihe River Basin are used.

One downscaling method is the simple stochastic method, where the rainfall on rainy days is set to be equal to the average daily intensity within a month and there is no variability in rainfall intensity between rainy days. The magnitude of rainfall on rainy days can be expressed as

$$P_I(I) = P_m / P_d, \qquad (I = 1, 2, \cdots, P_d) \tag{3}$$

where $P_I(I)$ is the rainfall intensity in rainy days; P_m is the monthly precipitation; P_d is the number of rainy days in a month.

The number of rainy days in any month is estimated using an empirical relationship developed from rainfall data in the Huaihe River Basin. The relationship can be quantitatively expressed as

$$P_d = \frac{2DN(J)}{\pi} \mathrm{Arctg}(AP_m + B), \tag{4}$$

where P_m is the magnitude of rainfall in a month; $DN(J)$ is the number of days in any month ($J=1,2,\cdots,12$); A and B are coefficients, which can be obtained from the analysis of the observed daily rainfall data.

Another method stochastically generates the rainfall intensity in the rainy days from an exponential distribution

$$F(x) = \alpha e^{-\beta x}, \tag{5}$$

where x is the magnitude of rainfall on rainy days; α and β are coefficients. Thus the rainfall amount in rainy days can be expressed as

$$x_i = F^{-1}(u_i) = -\alpha_1 \ln(u_i) + \beta_1, \tag{6}$$

where F^{-1} is the inverse function of F; u_i is uniform $[0,1]$ random number; α_1 and β_1 are coefficients.

In both methods, the generated monthly sum is constrained to be equal to the monthly rainfall. And the probability of rain on any day is considered to be equal. Therefore, the generated daily precipitation is distributed at random through a month.

3. *Application of the Downscaling Method in the Hydrological Model*

The downscaling methods described in Section IV-2 are applied to the area upstream of Bengbu in the Huaihe River Basin with the area of 121 330 km^2. The model spatial resolution is still 30 km×30 km. There are totally 153 grid cells. The inputs to the model are monthly precipitation P_m and monthly evaporation E. The model outputs are accumulated to monthly discharge. Research area is divided into 11 sub-areas.

The Xin'anjiang Model is run in three situations:

A. Model is run at monthly time step with observed monthly input;

B. Using uniform method to generate daily precipitation from monthly data, then the model is run at daily time step;

C. Using exponential distribution method to generate daily precipitation from monthly data, then the model is run at daily time step.

Model output is at a monthly resolution in all the situations (Table 2).

Table 2. Model Results in Different Situations

Sub-area	Station	Efficiency (A)	Efficiency (B)	Efficiency (C)
1	Xixian	0.8768	0.9244	0.9173
2	Bantai	0.8504	0.8536	0.8764
3	Luohe	0.8515	0.8386	0.8307
4	Zhoukou	0.8680	0.8404	0.8477
6	Jiangjiaji	0.8438	0.8682	0.8698
7	Hengpaitou	0.6632	0.842	0.84
8	Fuyang	0.8525	0.7842	0.8157
9	Wangjiaba	0.8007	0.8632	0.87
10	Lutaizi	0.7621	0.9245	0.9273
11	Bengbu	0.6504	0.9095	0.9127
	Average	0.8019	0.8649	0.8708

It can be seen from Table 3 that the average model efficiencies of schemes A, B and C are 0.8019, 0.8649, and 0.8708 respectively. When the Xin'anjiang Model is run at daily time step from the monthly data, the model results are more accurate than the monthly hydrological model. The results of the exponential distribution method are a little bit better than the uniform one. For both methods, the probability of rainy day distribution is considered to be equal. So the generated daily precipitation is distributed at random through a month, and the estimation of runoff will change with the precipitation distribution. In the future study, the generated daily precipitation should be distributed more reasonably based on the analysis of observed data.

Figure 4 shows the distribution of the simulated runoff with the inputs of downscaled precipitation data (exponential distribution downscaling method) in the Huaihe River Basin in October 1953. Compared with Fig. 3, it can be seen that the runoff is calculated in most grid cells while running the daily hydrological model by use of the downscaling method.

V. CONCLUSION AND DISCUSSION

In this paper, a monthly grid-based macroscale hydrological model has been developed based on the Xin'anjiang Model in order to assess the effects of climate change on water resources, the monthly discharge from 1953 through 1985 in the Huaihe River Basin has been quite well simulated with this model.

Due to the increase of time interval and decrease of precipitation intensity within a month, there will have no monthly runoff in some girdded cells as the monthly

																			5											
																		26	18	23	22									
												1	2	3	5	4	14	14	23	23	21									
											1	1	2	3	4	7	22	17	14	15	21	16	16							
										2	2	2	2	5	4	7	7	11	11	13	22	16	16							
									2	4	2	2	6	5	7	5	5	6	6	10	6	20								
				3	1	0	0	5	3	2	4	3	3	3	5	3	5	6	6	4	6	20	19	13						
		2	4	4	0	1	1	1	3	3	4	3	3	3	3	3	3	5	3	4	8	20	3	13	3	4				
	2	3	1	1	2	1	1	1	4	4	4	3	3	3	3	3	7	4	3	2	8	4	3	2	4	4				
2	2	4	0	0	3	1	0	1	5	5	4	5	5	5	3	2	2	1	2	2	6	4	4	2	8	7	7			
2	4	4	1	1	1	1	0	4	4	3	4	4	4	3	2	4	2	2	5	5	6	2	2	1	9	7	2			
			4	4	5	1	0	0	4	2	2	5	4	6	5	3	3	2	2	2	2	2	2	2	9	2	2	2		
				3	4	1	3	3	1	3	2	5	4	8	8	3	2	1	1	1	1	2	4	5	4	2	2	5		
				2	2	1	3	3	2	1	3	1	1	8	4	4	2	1	1	1	5	5	2	5	5	4	6	6	6	14
				3	2	1	0	0	1	0	3	2	1	1	4	8	7	4	1	1	5	4	4	6	4	6	6	6	14	14
				3	2	1	1	1	1	1	3	3	1	1	6	8	1	1	1											
					3	2	1	6	2	2	4	4	2	2	9	6	3													
						1	1	6	6	9	6	12	9	8	9															
								7	7	13	11	12	23	18																
											10	19	36	37																
													36	37																

Fig. 4. Distribution of the simulated runoff in the Huaihe River Basin in October 1953 with the inputs of downscaled precipitation data.

hydrological model is applied to the Huaihe River Basin. Two methods of downscaling monthly precipitation to daily resolution are validated by running the Xin'anjiang Model at daily time step from the monthly data, and the simulation results show that the model outputs are more realistic compared with the monthly hydrological model. And this may indicate that, when assessing the impact of the climate change on water resources, the daily hydrological model can be used instead of the monthly one.

In spite of the relative success of conceptual macroscale hydrological modeling for its application to the climate impact studies, its final value in the coupled continental scale land-atmosphere modeling is still unclear, due to the lack of energy balance components and without further considerations in vegetation in the conceptual model. Full coupling of hydrological models and climate models requires that both the water balance and the energy balance be solved.

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