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A distributed runoff model for inland mountainous river basin of Northwest China

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In order to predict the futuristic runoff under global warming, and to approach to the effects of vegetation on the ecological environment of the inland river mountainous watershed of Northwest China, the authors use the routine hydrometric data to create a distributed monthly model with some conceptual parameters, coupled with GIS and RS tools and data. The model takes sub-basin as the minimal confluent unit, divides the main soils of the basin into 3 layers, and identifies the vegetation types as forest and pasture. The data used in the model are precipitation, air temperature, runoff, soil weight water content, soil depth, soil bulk density, soil porosity, land cover, etc. The model holds that if the water amount is greater than the water content capacity, there will be surface runoff. The actual evaporation is proportional to the product of the potential evaporation and soil volume water content. The studied basin is Heihe mainstream mountainous basin, with a drainage area of 10,009 km2. The data used in this simulation are from Jan. 1980 to Dec. 1995, and the first 10 years´ data are used to simulate, while the last 5 years´ data are used to calibrate. For the simulation process, the Nash-Sutcliffe Equation, Balance Error and Explained Variance is 0.8681, 5.4008 and 0.8718 respectively, while for the calibration process, 0.8799, -0.5974 and 0.8800 respectively. The model results show that the futuristic runoff of Heihe river basin will increase a little. The snowmelt, glacier meltwater and the evapotranspiration will increase. The air temperature increment will make the permanent snow and glacier area diminish, and the snowline will rise. The vegetation, especially the forest in Heihe mountainous watershed, could lead to the evapotranspiration decrease of the watershed, adjust the runoff process, and increase the soil water content.

A distributed runoff model for inland mountainous river basin of Northwest China CHEN Rensheng1,2, KANG Ersi1, YANG Jianping1, ZHANG Jishi1 (1.Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou 730000, China; 2.Remote Sensing and GIS Institute, Peking University, Beijing 100871, China) 1 Introduction The arid area of Northwest China lies in the inland area of Asia far from oceans. It consists of several large inland river basins. Many enormous mountain ranges lie in the area and the uplift air current containing water vapor, making the mountainous area receive much more precipitation compared with the lowland area in front of the mountains. Glaciers and snow storage develop very well in the mountains. Therefore, in an inland basin of Northwest China, mountainous watersheds are runoff generation areas, while the lowland plains, basins and deserts in front of the mountains are the areas of water resources consumption and runoff scattering. Thus, the runoff amount generated from the mountains, which runs out of outlets of the mountainous watersheds, basically represents the amount of water resources of the inland arid area (Kang et al., 1999). Now the oases in Northwest China are diminishing, while the deserts are expanding (Feng et al., 2000). Therefore, it is very significant to forecast the runoff amount from mountainous area. For water management, environmental conservation and other applications, monthly runoff amount forecasting may be more important (Zhang et al., 2000). Runoff production is a complicated process that is believed to be nonlinear, time-varying, spatially distributed (Singh, 1964; Beven et al., 1979; Anderson et al., 1990; Peter et al., 1993; Mark et al., 1994; Aronica et al., 2000). Three major approaches for runoff estimation have been explored in the literature, namely an empirical black box model or a system theoretic model, a deterministic model or a physically based distributed model, and a lumped conceptual model (Anderson et al., 1985; Dooge, 1979; Woolhiser et al., 1982). The lumped conceptual model has a conceptual framework, requires a few variables and a little computational time. The system theoretic model has si mple structure, requires a few variables, and often produces favored results (Hsu et al., 1995; Gautam et al., 2000; Ratkovich et al., 1999; Ratkovich, 2000). However, both the 2 kinds of models are not spatially distributed, they could not analyze the effects of underlying surface, such as soil type, land use, human activity, vegetation, etc. Nevertheless, in a large basin, the huge data that the physically based distributed model requires are often not feasible, and the results that the distributed model produces are often unfavorable (Dooge, 1979; Peter et al., 1993; Mark et al., 1994). In order to approach to the effects of vegetation on runoff production processes of a large basin in Northwest China, only the normal data from several hydrometric stations are used can a conceptual distributed parameter runoff model be selected. 2 Study area Heihe river, originating from the Qilian Mountains, running through Hexi Corridor and scattering in the deserts, is one of the largest inland rivers in Northwest China, with a drainage area of 130,000 km2. The water vapor current comes mainly from the summer southeast monsoon from the Pacific Ocean and the summer southwest monsoon from the Indian Ocean (Zhou, 1983; Sun, 1977), next from the western air current (Yang, 1992). In winter, it is extremely cold and dry because of the dominant control over the area by the Mongolia and Siberia High. Therefore, the Heihe river basin is climatically dry and short of water resources. Heihe river basin, like other inland river basins in Northwest China, possesses distinctive vertical zonality of landscape, i.e., the mountainous area and the area in front of the mountains. The former can be divided into the high mountain ice, snow and permafrost zone and the mountain vegetation zone, while the latter can be divided into oases zone and desert zone (Kang et al., 1999). As a case study, we take the Heihe mainstream mountainous watershed as an example. The mountainous catchment of Heihe mainstream, ranging from 1,674 m to 4,823 m in altitude, has a drainage area of 10,009 km2. The runoff generated from this watershed is controlled by Yingluoxia hydrometric station (38o48´N, 100o11´E), which controls about 55% of the total runoff in Heihe river basin. In or near the watershed, there are 6 other hydrometric stations, named Qilian (38o12´N, 100o14´E), Tuole (38o49´N, 98o25´E), Sunan (38o50´N, 99o37´E), Minle (38o27´N, 100o49´E), Zhamashike (38o59´N, 99o14´E) and Yeniugou (38o25´N, 99o35´E) respectively (Figure 1 and Table 1). In Heihe mainstream mountainous region, there is little cropland and population, no reservoirs. 3 Model description As there are only 7 hydrometric stations in or near the watershed, and the time step is a month, the model use sub-basin as the minimal unit. The input data are meteorological data, soil data, vegetation data, land use data etc. Based on the 1:100,000 digital geographic map and GIS tools, the entire study area is divided into 103 sub-basins, and the area, perimeter, average altitude, average slope, and the center coordinate (Gauss projection) of each sub-basin are calculated. 3.1 Input data 3.1.1 Hydrometric data Monthly precipitation data come from all the 7 stations (Figure 1). The average monthly air temperature data and the ?准20 evaporation pan data are observed at Minle, Sunan, Qilian, Yeniugou and Tuole. The simulated monthly runoff is the observed runoff at Yingluoxia hydrometric station. All the data are ranging from January 1980 to December 1994. 3.1.2 Soil data Figure 2 is the soil type image, which comes from actual investigation. The model simplifies that each sub-basin has only one type of soil. At last 7 main types of soils are chosen. According to investigation results, all the soils are divided into 3 layers, i.e., H-layer, transitional layer and parent layer. The soil depth, bulk density, voidage and soil weight water content of each soil layer are surveyed (Table 2).

3.1.3 Land cover data Figure 3 shows the land cover types of the studied watershed, which are generated from the subscene acquired in 1995 by Landsat TM4. Based on the field investigation, the author gets the coverage of each main land cover (Table 3). From Figure 3 and the investigated coverage data, we can get the snow and glacier area, bare land area, and vegetation coverage area. The model divided each sub-basin into 3 kinds of land cover, that is bare land, vegetation region and snow and glacier area, and simplifies all the vegetation that are classified into 2 types, forest and pasture. Each subarea of a sub-basin has its own hydrological processes. 3.2 Model mechanism The meteorological variables and soil data are arbitrarily uniform in a sub-basin, that is, in bare land region, in forest region, in pasture region or in glacier region of a sub-basin, the precipitation for example, is equal. 3.2.1 Sub-basin meteorological data In an inland river basin of Northwest China, the monthly precipitation has high linear relationship with altitude, longitude and latitude, so does the average air temperature and evaporation capacity (Kang et al., 1999). In the model, the authors obtain the relationship of each month´s data, using the algorithm described by Levenberg (1944), and calculate the monthly precipitation, average monthly air temperature and monthly evaporation capacity of each sub-basin in January 1980 to December 1994. 3.2.2 Solid and liquid precipitation separation Use critical air temperatures T_l and T_s to separate the monthly precipitation into snowfall and rainfall (Kang et al., 1999): $T_0 < T_s$ $P_s = P$ $T_0 > T_l$ $P_l = P$ $T_s < T_0 < T_l$ $P_s = (T_0 - T_s)*P / (T_l - T_s)$ (1) where T_0 is the averaged monthly air temperature, T_s is the critical air temperature for snowfall, T_l is the the critical air temperature for rainfall, P_s is snowfall, P_l is the rainfall, and P is total precipitation. 3.2.3 Precipitation correctness The observed precipitation has systematic error (Yang, 1999), and should be corrected. The model gives 2 corrective parameters for snowfall and rainfall res pectively. 3.2.4 Canopy interception Table 4 shows the average canopy interception ratio of forests and pasture observed in the watershed in 1985-1995. The model set 4 adjusts parameters to correct the data for different vegetation types and different precipitations (snowfall or rainfall). 3.2.5 Seasonal snowmelt Seasonal snowmelt is also calculated according to critical air temperature (Kang, 1999). The methods are, if the average maximal monthly air temperature is lower than the critical value, there will be no snowmelt, the snowfall in this month will be accumulated. If the average minimal monthly air temperature is higher than the critical value, the seasonal snowfall in and before the month will be melted completely. Otherwise, there will be part snowmelt water. 3.2.6 Glacier meltwater The glacier in Northwest China is continental glacier (Wang, 1981), therefore, the meltwater comes mainly from the surface of the glacier. The critical air temperature method for glacier melt is similar to seasonal snowmelt. Considering the glacier has a different surface emissivity versus seasonal snowfall, the glacier meltwater is given an adjusting parameter GGF. 3.2.7 Actual evapotranspiration The actual evapotranspiration is proportional to the product of the potential evaporation and soil volume water content. To different soil types, different land covers, the model gives a parameter to control. 3.2.8 Sub-basin runoff production In a sub-basin, if any, there are 4 sub-regions, that is, bare land, forests, pasture and glaciers. Each sub region has its own hydrological processes. 1) Some concepts Introduce and define some concepts that will be used in the following parts: Soil volume water content Wv (%), water retaining capacity W (mm), storage capacity Wc (mm) and storage coefficient Wratio. where s is soil bulk density (g/cm3), Wg is soil weight water content (%), H is soil height (cm), and ?兹 is soil voidage (%). 2) Bare land runoff production H-layer where Rs1 is runoff from H-layer (mm), Sinput is the net liquid water to the H-layer (mm), that is liquid precipitation and seasonal snowmelt, W1 is the initial water retaining capacity for H-layer (mm), and Wc1 is the Wc for H-layer (mm). If Rs1 is greater than 0, there will be surface runoff in H-layer, and at this time W1′ =Wc1, where W1′ is the new W for H-layer. Otherwise, there is no surface runoff and W1′ = Sinput+W1. Some of the W1′ will evaporate, some will leak to the transitional layer, and of course, the rest will store up in H-layer. The model arbitrarily considers that the leakage process takes place firstly, while the evaporation process secondly. The leakage process can be described as: where Wratio1 and Wratio2 is the Wratio for H-layer and transitional layer respectively, 0 < f1gra< 1, is a parameter about gravity leakage from H-layer to transitional layer, Winf1 is the seepage amount from H-layer to transitional layer (mm), W2 and Wc2 is the W and Wc for transitional layer (mm) respectively. From Eqn. 8: where W for H-layer and transitional layer is W1´-Winf1 and W2+Winf1. The model assumes that only the moisture in H-layer could be evaporated. The soil evaporation Es (mm) for bare land region is: where E0 is ?准20 evaporation pan data (mm), H1 is soil height of H-layer (cm), while Efs is the parameter that adjusts the soil evaporation for different soil types. At this time, the W of H-layer is W1´-Winf1-Es. Transitional layer Rs2＝W2+Winf1-Wc2 (11) where Rs2 is runoff from transitional layer (mm). If Rs2 >0, there will be interflow in transitional layer, and at this time W2´＝Wc2, where W2′ is the new W for transitional layer. Otherwise, there is no runoff, and W2´＝W2+Winf1. Now Wratio2´＝W2´/Wc2, Wratio3＝W3/Wc3, the leakage amount from transitional layer to parent layer Winf2 (mm) is: Winf2＝ (Wc3×W2´-f2gra×Wc2×W3) / (f2gra×Wc2-Wc3) (12) where Wc3 and W3 is the Wc and W of parent layer (mm), f2gra is the parameter about gravity leakage from transitional layer to parent layer. At this time, the W of transitional layer is W2´-Winf2, of parent layer is W3+Winf2. Parent layer Rs3＝W3+Winf2-Wc3 (13) where Rs3 is runoff from parent layer (mm). If Rs3 > 0, there will be interflow in parent layer, and at this time W3´＝Wc3, where W3′ is the new W for parent layer. Otherwise, there is no runoff, and W3´＝W3+Winf2. The model supposes that the water leak from parent layer would directly to ground water. The leakage amount Winf3 (mm) can be defined as: Winf3＝fInf×W3´ (14) where fInf is a parameter. Now the W of parent layer is W3´-Winf3. 3) Forest and pasture region runoff production In forest and pasture region, the net liquid input water is intercepted liquid precipitation and seasonal snowmelt water. Of course the evapotranspiration is different from the bare land region. Other hydrological processes are the same as those of the bare land region. 4) Glacier region runoff production Rg＝GRF×(Ginput+ Gd) (15) where Rg is the runoff from glacier surface (mm), Ginput is the net liquid water to the glacier surface (mm), Gd is the glacier melt water (mm), and GRF is a parameter. 3.2.9 Base flow Q_base_i = k_r×Pi (16) where Q_base_i and Pi is the base flow and precipitation in sub-basin i (mm), k_r is a parameter. 3.2.10 Runoff accumulation Q = Qi + Q_c(17) Qi=(Rsi×Sareai+Rmui×muareai+Rcaoi×caoareai+Rgi×Gareai+Q_base_i×B_areai)/(day×86400×1000) (18) where Qmod is runoff of the total studied watershed (m3/s), Qi is the runoff produced in sub-basin i (m3/s), Q_c is the base flow constant (m3/s), Rmui, Rcaoi, Rsi and Rgi is runoff from forest region (if any), pasture region, bare land region and glacier region (if any) in sub-basin i (mm) respectively, Sareai, muareai, caoareai and Gareai is the area of forest region, pasture region, bare land region and glacier region in sub-basin i (m2) respectively, B_areai is the area of sub-basin i (m2) and day is the number of days in each month. 3.3 Model evaluation criteria Three evaluation functions are selected as evaluation criteria. One is the famous Na sh-Sutcliffe Equation NSE (Nash et al., 1970): NSE = 1 - (19) where Qiobs is the observed hydrological series for time i, Qimod is the calculated hydrological series for time i, is mean observed hydrological series, and n is the length of the series. A model is more efficient when NSE is closer to 1 (Loumagne et al., 1996). The second criterion is the balance error B over whole record (Loumagne et al., 1996): B = 100 % (20) B may be positive or negative, and if B is close to zero, there will be little balance error. Explained variance EV is also a performance criterion (Marco et al., 1991), where EV = 1 - (21) with is mean of the (Qobs-Qmod). If EV is close to 1, the model error is very little (Marco et al., 1991). EV may be a large positive value. 4 Results and discussion 4.1 Results As described in section 3.2.1, all the hydrometric data are ranging from January 1980 to December 1994. The data obtained from January 1980 to December 1989 are used for the simulation process, while those from January 1990 to December 1994 are for model validation (Figures 4 and 5). The simulation results are very well, with NSE = 0.8681, B = 5.4008 and EV = 0.8718. The validation results are also very well, NSE = 0.8799, B = -0.5974 and EV = 0.8800. Therefore, the model structure is suitable to the study basin, and the parameters of the model also fit in the study region (Table 5). 4.2 Vegetation effects From the above description, the model results are well. Thus, the authors set some scenes to approach the effects of vegetation to hydrological processes. The scenes are that, the entire watershed is covered with forests, with pasture or with no vegetation. According to these scenes, the authors use the model to calculate the evapotranipiration, runoff and the watershed water content (Figures 6-8). The watershed evapotranspiration will be the most if the watershed is covered with no vegetation; it will be larger if covered with pasture completely; and it will be the least if covered with forests. The watershed runoff amount and peak flood will be the most if there is no vegetation in the watershed (Figure 7), but both will be the least if covered with forests. The watershed water content will be the most if the watershed is covered with forests completely, and it will be the least if there is no vegetation (Figure 9). 4.3 Effects of global warming The global warming will overall cause the increase of the evaporation and transpiration from the earth surface; therefore the precipitation will increase as a whole (Kang et al., 1999). The simulation with the present climate models indicates that the averaged increase of air temperature of the earth´s surface by 1.5-4.5oC will cause an increase of global averaged precipitation by 3-15% (Amell et al., 1996). Nevertheless, the spatial and temporal distribution of precipitation on the earth´s surface is extremely uneven, when precipitation increases in some regions, it may decrease in other regions (Amell et al., 1996). Shi et al. (1995) state that the averaged air temperature may increase 1.5±1oC to the year 2030, while increase 1±0.5oC in mountain area of Northwest China. Based on the results of glacier analysis, Shi et al. (2000) also pointed out that the averaged air temperature in mountainous area might increase 0.4-1.2 to 2030 in Northwest China. Therefore, the authors assume several scenarios that may happen to 2030 to predict the monthly runoff changes, based on the averaged data in 1957-1995. The climatic scenarios are: the precipitation does not change, the air temperature increases 0.5oC, 1.0oC and 2.0oC; the air temperature does not change, the precipitation increases 10% and 20%; the air temperature increases 0.5oC and the precipitation increases 10%. Firstly, simulate the mean monthly runoff of 1957-1995 at Yingluoxia station, using mean hydrometric data in 1957-1995 with runoff model and parameters in Table 5. The simulation results are very well, NSE = 0.9556, B = 2.8803 and EV = 0.9569. Then calculate the error between the simulated and the observed runoff. Finally, calculate the futuristic runoff in different scenes. In this case, the predicted results should minus the above simulating error (Figure 9). From Figure 9, if the air temperature increases a little while the precipitation does not change, the runoff in April and May will increase, because of the increased snowmelt and glacier-melt. However, the runoff in June to September will decrease because of the increasing evapotranspiration. In winter, if the air temperature increases less than 1oC, the runoff will not change. Otherwise, the winter runoff will increase a little. The yearly runoff will decrease a little if just the air temperature increases. If futuristic precipitation increases a little while the air temperature does not change, the yearly runoff will increase, especially in summer. 5 Conclusions In order to simulate monthly runoff from mountainous region of Northwest China, and to research effects of some hydrological processes to the environments, the authors give a distributed parameter runoff model. The simulation and calibration processes of the model are very well when it is used in Heihe mainstream mountainous watershed. Under the global warming scenes, the futuristic runoff of Heihe river basin will increase a little. The snowmelt and glacier meltwater will increase, and the evaportranspiration will also increase. For the air temperature increment, the permanent snow and glacier area will diminish, and the snowline will rise. The model results show that the vegetation in mountainous basin of Northwest China, especially the forests, could lead to the actual evapotranspiration decrease, peak flood adjustment, runoff amount decrease and the water content of the basin increase.

关键词： inland river; mountainous basin; distributed runoff model; vegetation; Heihe River