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A COMPARATIVE STUDY OF A SWEDISH AND A CHINESE HYDROLOGICAL MODEL[1]

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ABSTRACT: There are a large number of conceptual hydrological models available today. It is not easy to immediately identify the similarities and differences between the different models. The Swedish HBV model and the Chinese Xinanjiang model are two examples of conceptual, semi-distributed, rainfall-runoff models. The Xinanjiang model was designed for use in humid and semi-humid regions, with no routine for the snowmelt runoff, whereas the snow routine is an important part of the HBV model in many applications. The model structures of the two models may be described in four routines, compared in this paper. The integral structures of them are similar, but there are some differences, especially in the runoff production routine. The physical significance and physical definitions of some model parameters were analyzed. Both models were tested in two basins. Both models gave similar results, and both models performed well in the application. The similarity of the results obtained by different model structures leads to the following two conclusions. First, more effort should probably be spent on the improvement of input data quality and coverage than on the development of more detailed model structures only. Second, inference about basin behavior and characteristics from the values of calibrated model parameters must be made with great caution.
(KEY TERMS: conceptual models; model comparison; HBV model, Xinanjiang model.)

INTRODUCTION

Conceptual hydrological models have become more and more popular and play a major role in hydrology today. Most of them were originally developed for flood forecasting, but they have since then found many other applications. There are a large number of hydrological models in the world. Water balance considerations and simplified descriptions of the elements in the hydrological cycle are common to all models. It is, nevertheless, often difficult to immediately identify the differences and similarities between the different models. A number of model intercomparisons have been carried out by the World Meteorological Organization (e.g., WMO, 1975, WMO, 1986, and WMO, 1992). These intercomparisons have mostly focused on the performance of the models in applications and have not emphasized the model structures. An intercomparison can reveal merits and demerits of the models and also point to possibilities for further model development.

The objective of this paper is to make a more detailed intercomparison between two selected models, namely the Swedish HBV model (Bergström, 1976 and 1992) model and the Chinese Xinanjiang model (Zhao, 1992). Both of the models are rainfall-runoff models, although the HBV model also has a snow routine. The emphasis was put on model structure, but examples of applications are also presented.

GENERAL STRUCTURE OF THE HBV MODEL

The HBV model (Bergström, 1976 and 1992) is a conceptual hydrological model (Figure 1). In different model versions it has been applied in some 30 countries all over the world, with such different climatic conditions as Sweden, Zimbabwe, India, and Colombia. Although the HBV model has a routine for snow accumulation and melt, this routine was not studied in the intercomparison and will not further be described here. The model can be used as a semi-distributed model by dividing the area into subbasins. Each subbasin is then divided into zones according to altitude, lake area, and vegetation. The model is normally run on daily values of rainfall and air

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temperature, and daily or monthly estimates of potential evaporation. The model is used for flood forecasting and many other purposes, such as spillway design floods simulation (Bergström *et al.*, 1992), water resources evaluation (e.g. Jutman, 1992; Brandt *et al.*, 1994), etc. A more complete description of the model was given by Bergström (1992).

The soil moisture routine determines the runoff coefficient and the actual evaporation. Both the runoff coefficient and the actual evaporation are uniquely related to the soil moisture storage, and they increase with increasing soil wetness. There is a maximum capacity, *Fc*, of the soil moisture storage. When this value is reached, each mm of rainfall will contribute to runoff. The outflow from the soil routine is routed, without delay, to the upper tank of the runoff distribution routine. In this routine, the distribution in time of the runoff, i.e., the shape of the hydrograph, is determined. A constant percolation to the lower tank takes place as long as there is water in the upper tank. The upper and lower tanks produce the quick response and base flow respectively.

GENERAL STRUCTURE OF THE XINANJIANG MODEL

The Xinanjiang model (referred to as the X model in this paper) was developed in 1973 and published in 1980 (Zhao *et al.*, 1980; Zhao, 1992). Its general structure is given in Figure 2. It has been applied successfully over very large areas, including most of the agricultural, pastoral, and forested lands of China, except the loess. It has also been tested in some other countries, such as the United States, Germany, and France, and some Asian countries. In China, the X model is used mainly for hydrological forecasting.

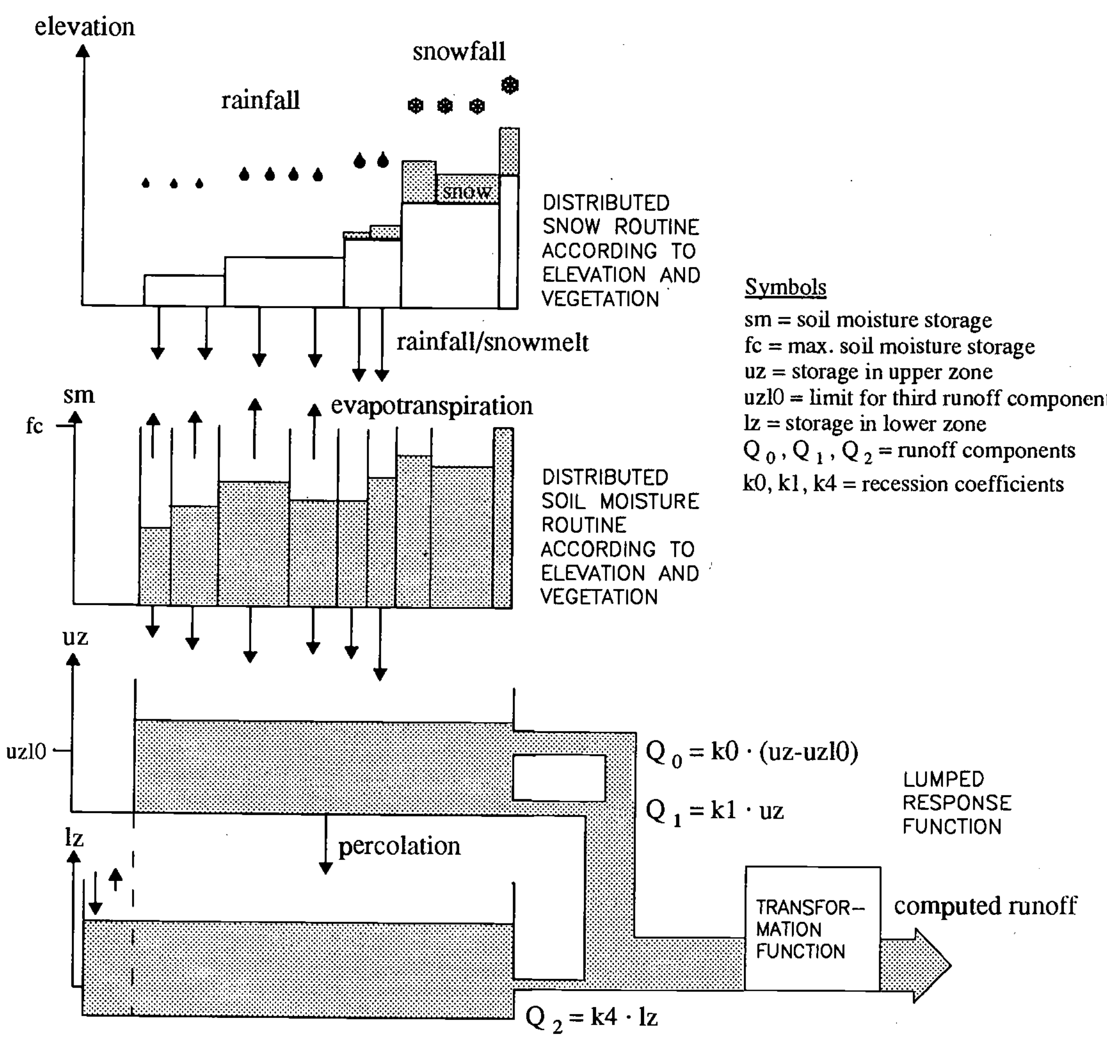

Figure 1. The General Structure of the HBV Model as Applied to One Subbasin.

Recently the model is also being used for some other purposes, such as water resources evaluation, hydrologic network station planning, etc. The X model is a rainfall-runoff, distributed basin model used in humid and semi-humid regions. There is no snowmelt routine in the model. The basin, in which the X model is applied, is divided into a set of sub-basins by Thiessen polygons or according to geographic and geological elements.

There are four routines in the model. First, the runoff *R* of each subbasin is calculated. The principle is runoff formation with the repletion of soil moisture storage, which means that runoff is not produced until the soil moisture content of the aeration zone reaches field capacity, and thereafter runoff equals the rainfall excess without further loss. This is the main feature of the model. Second, the total runoff, *R*, in each subbasin is divided into three components: *RS*, surface runoff; *RI*, the contribution to interflow; and *RG*, ground water. To simulate this separation, a tank of free water storage is used. Third, the different damping effects of the runoff components occurring on the hillside of the basin are simulated by linear reservoirs. To simulate the flow concentration in the channel network within the subbasin, the convolution of empirical unit hydrograph or the "lag and route" method with parameters *L* and *CS* is adopted. In the empirical unit hydrograph, the empirical ordinates are calibrated manually, in a trial-and-error procedure. Finally, the flow concentration from each subbasin outlet to the total basin outlet is achieved by applying the Muskingum method.

COMPARISON BETWEEN THE TWO MODELS

Soil Moisture Routine

The runoff is produced in the soil aeration zone in both the X model and the HBV model. The measured precipitation minus the actual evaporation and runoff is the increment of the soil moisture storage. This balance equation can be solved for each time step, giving the actual evaporation of the basin and runoff.

Evaporation. The most important difference between the evaporation computation in the two models is that the X model uses three different layers in the soil whereas the HBV model uses one layer only. There are, nevertheless, applications of the HBV model where a horizontally layered soil routine has been used (e.g., Lindström and Rodhe, 1992), and applications with an interception storage which resembles an upper soil layer (Lindström *et al.,* 1994).

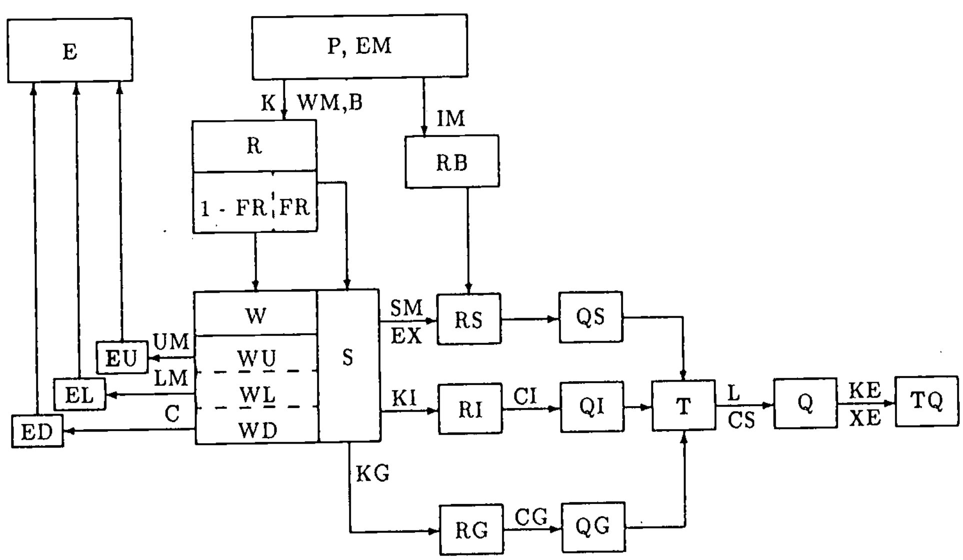

Figure 2. The Flow Chart of the Xinanjiang Model as Applied to One Subbasin (after Zhao, 1992).
E (EU, EL, ED): actual evapotranspiration from the whole basin, EU from upper soil layer, EL from lower and ED from deepest layer. P: areal mean rainfall. EM: measured pan evaporation. IM: impervious area. R (RS, RI, RG): runoff from pervious area with components RS (surface runoff), RI (interflow), and RG (ground water flow). FR: variable runoff producing area. W (WU, WL, WD): areal mean tension water storage with components WU, WL, and WD in the upper, lower, and deeper components, respectively. S: areal mean free water storage at a point. Q (QS, QI, QG): discharge from a subbasin with components QS, QI, and QG, surface runoff, interflow, and ground water, respectively. T: total subbasin inflow to the channel network.

The evaporation mechanisms of the two models are schematically illustrated in Figures 3 and 4. In both of the models, the actual evaporation, E, is equal to the potential, EM, when the total wetness is near field capacity. This range is denoted in the Figures 3 and 4 as the range between x and y. During a dry period, the soil moisture will decrease similarly in the two models, due to the evaporation. This is the area to the left of y in the figures, where the actual evaporation is related to the relative soil moisture storage, W/WM in the X model and Ssm/Fc in the HBV model. WM and Fc are model parameters, and W and Ssm are the total water content. A slight difference is that in the X model, E is constant when the soil wetness is below z, whereas the evaporation in the HBV model ceases.

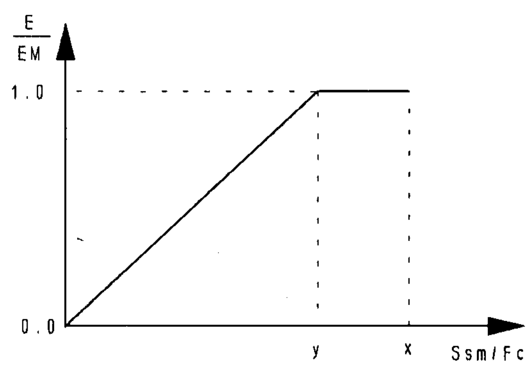

Figure 3. The Evaporation Mechanism of the HBV Model, where *Ssm* is the Soil Moisture, *Fc* is the Capacity of *Ssm*, *E* is the Actual Evaporation, and *EM* is the Potential Evaporation Rate.

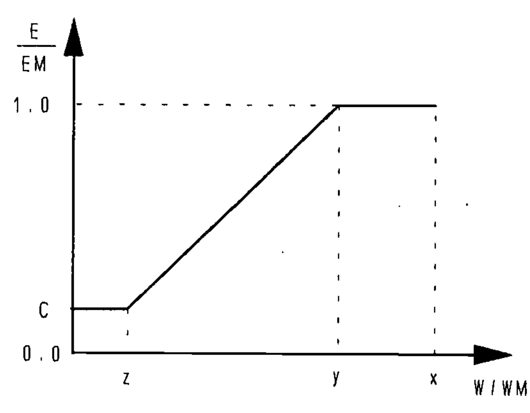

Figure 4. The Evaporation Mechanism of the Xinanjiang Model, where *W* is the Total Soil Moisture, *WM* is the Capacity of *W*, *E* is the Actual Evaporation, and *EM* is the Potential Evaporation Rate. The curve is strictly valid for the drying phase only.

However, when rainfall begins again after a dry period, the water will first be retained in the upper layer of the X model. The evaporation from this layer is always potential, which means that high evaporation will occur immediately after a rainfall event. The schematic representation in Figure 4 is therefore valid for the drying phase only. In the HBV model, the low soil-moisture storage will result in a low evaporation, since the total soil-moisture storage determines the evaporation.

The field capacity parameters, Fc and WM, express the tension soil moisture. They have the same physical definitions, which means that their values are equal to the maximum soil moisture that can be evaporated back into the atmosphere. However, in practice, Fc is usually larger than WM. This could be because of the difference mentioned above in the evaporation computation. Thus, we should be very careful when the computed soil moisture of a model is adopted as a real physical value. A better variable to use might be the soil moisture deficit – i.e., the difference between the soil moisture capacity and the actual soil moisture – as a physical value rather than the soil moisture itself.

Runoff Coefficient. The runoff generation is related to the water content in the soil moisture zones of both models. In the X model, runoff production occurs only on the repletion of tension water storage at a point in the basin. To provide for a non-uniform distribution of tension water capacity, a curve is used. These two points are the essential hypotheses for the runoff production of the X model. The coefficient of runoff can be derived as:

$$\frac{dR}{dP} = \frac{f}{F} = 1 - \left(1 - \frac{W}{WM}\right)^{\frac{B}{1-B}} \qquad W < WM$$

$$\frac{dR}{dP} = 1 \qquad W \geq WM \qquad (1)$$

where B is a parameter, W is tension soil moisture, R is runoff, P is rainfall, F is the total area of a subbasin, and f represents the pervious area of F. The runoff mechanism of the HBV model is simpler. Here also, it is assumed that there is a distribution of soil types and thicknesses that leads to an increasing contributing area with increasing wetness in the basin (see Bergström, 1976). In the model this is described by the relationship

$$\frac{dQ}{dP} = \left(\frac{Ssm}{Fc}\right)^{\beta} \qquad Ssm < Fc$$

$$\frac{dQ}{dP} = 1 \qquad Ssm \geq Fc \qquad (2)$$

where Q means runoff and is equivalent to R in the X model, Ssm means actual soil moisture storage and is equivalent to W in the X model, Fc is the field capacity of the basin, equivalent to WM in the X model, and β is a free parameter whose function is similar to that of B of the X model. Comparing the two models, there are four common grounds:

1. The relationship between the coefficient of runoff and soil moisture is represented as an exponential function;
2. The runoff production is independent of the rainfall intensity;
3. All rainfall contributes to runoff when $W = WM$ in the X model and $Ssm = Fc$ in the HBV model;
4. The coefficient of runoff tends to zero when the soil moisture storage tends to zero.

The coefficient of runoff as a function of soil moisture of the two models is shown in Figure 5. The figure indicates that the two models behave similarly, with a gradual increase in runoff coefficient with increasing wetness.

Separation of Runoff Components

The runoff distribution components of the two models are not exactly identical, although their structures are similar. Both of them have three runoff components. In the X model, the total runoff, R, is separated into the three components: RS, surface runoff; RI, *interflow*; and RG, ground water. To model this separation, the concepts of a free water storage, S, and a free water storage capacity SM are used. The distribution of SM is described by a parabola. These relationships can be derived as follows (Zhao, 1992):

$$RS = \left\{ PE - SM + S + SM\left[1 - \frac{PE + BU}{S'mm}\right]^{1+Ex} \right\} \frac{f'}{f} \qquad PE + BU < S'mm$$

$$RS = (PE + S - SM)\frac{f'}{f} \qquad PE + BU \geq S'mm \tag{3}$$

$$RI = S * KI * \frac{f}{F} \tag{4}$$

$$RG = S * KG * \frac{f}{F} \tag{5}$$

where BU and $S'mm$ are the heights corresponding to S and SM on the parabola, f' is the portion of f, and KI and KG are parameters.

The upper zone of the HBV model (Figure 1) is a quasi-linear tank with a threshold storage parameter UZL. Three runoff components – Q_0, Q_1 and $Perc$ – will flow out from the upper tank. $Perc$ is a free parameter, and Q_0 and Q_1 are computed as follows:

$$Q_0 = K_0 * (Suz - UZL) \tag{6}$$

$$Q_1 = K_1 * Suz \tag{7}$$

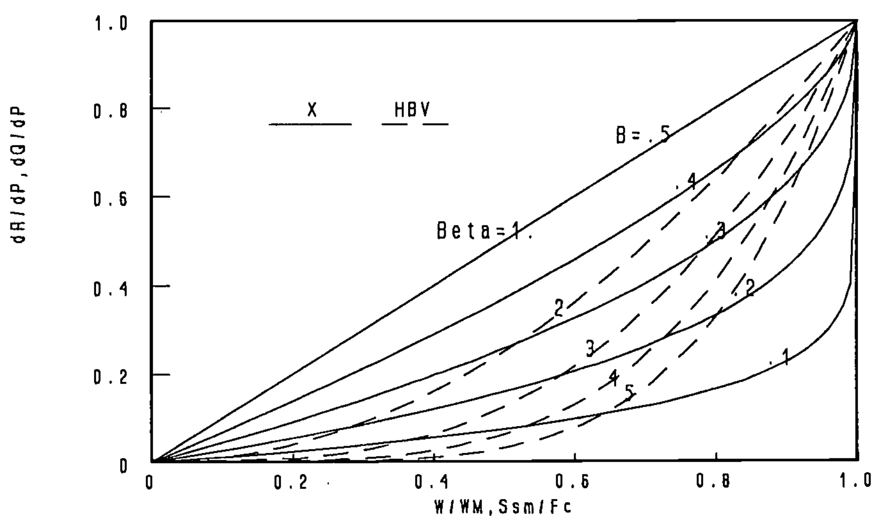

Figure 5. The Relation Between the Runoff Coefficient and Soil Moisture (solid lines represent the Xinanjiang model and the dotted lines the HBV model).

where K_0 and K_1 are recession rate parameters. When $Ex = 0$, $K_0 = 1$, $SM = UZL$ and $K_1 = KI$, the two models are nearly the same.

In the X model, the value of Ex is usually around 1 and surface runoff will occur as long as there is any runoff. In the HBV model, the flow Q_0 occurs when the storage Suz exceeds the threshold parameter UZL. Since $K_0 \leq 1$ in the HBV model, the flow Q_0 will be dampened compared with the outflow from the soil moisture routine, although the dampening is not so great. In the X model, this kind of damping action on surface runoff does not exist. The $Perc$ is a constant in the HBV model. It determines the amount of water, that percolates into the lower tank. In the X model, the ground water is directly proportional to the storage S at any moment.

Flow Concentration Within a Subbasin

The flow concentration within a subbasin can be divided into two stages, on the hillslope and in the channel network. Water flows down along the hillslope and forms the inflow to the channel system within the subbasin.

First, in the X model (Figure 2), it is assumed that we can neglect the damping on surface runoff RS; i.e., the RS passes through the hillslope unmodified to the channel system as TS. The interflow RI and the ground water RG are routed through linear reservoirs to the channel system as TI and TG individually. The damping of the interflow is less pronounced than that of the ground water. In the HBV model, additional damping in, for example, lakes, is achieved by the lower tank of the model. This is a linear tank, with inflow $Perc$ and outflow Q_2.

In the second stage, the runoff is concentrated in the channel system within the subbasin and then forms the outflow at the outlet of the subbasin. At this stage, all the runoff components behave in the same way. In the X model, the total inflow T of the channel network is convoluted through an empirical unit hydrograph or in the "lag and route" method with parameters L and CS to produce the subbasin outflow Q. The "lag and route" method means that the total inflow T is regulated by a linear reservoir first and then by a linear channel. The parameter CS acts as the linear reservoir. The parameter L acts as a linear channel, in that the hydrograph is moved backwards L time steps without affecting the shape. Recently, the "lag and route" method is adopted much more frequently than the unit hydrograph since it has two parameters only, and since calibration of the parameters is easier.

In the HBV model, a simple routing transformation is adopted in order to account for this time of concentration. It is a triangular distribution of weights with the base length $MAXBAS$ thus in effect a unit hydrograph. There are no essential differences between the two models in this routine.

Flow Concentration from Each Subbasin Outlet to the Total Basin Outlet

The Muskingum method is adopted in both of the two models.

TWO TEST APPLICATIONS

An important criterion of whether a hydrological model is realistic and efficient is its performance in application. The application can test the characters of the model structure and parameters synthetically. The suitability of the models can also be tested when the models are applied in different climatic regions. It has been proven that both the HBV model (Bergström, 1992) and the X model (Zhao, 1992) perform well in applications in a large number of very different basins. Here they were compared in two basins: Hushile, a Chinese basin; and Bird Creek, a basin in the United States. Neither of the basins has any snow in the winter.

The Hushile watershed is located in the middle eastern region of the People's Republic of China. It is a rolling terrain basin, located in a humid region. There is a good vegetative cover all over the basin. There are six rain gages in the basin and one pan evaporation observation station. Daily discharge data are available from the outlet of the basin. The Bird Creek basin is located in the central part of the United States. It was one of the basins in the simulated realtime intercomparison of hydrological models (WMO, 1992). It is a rolling terrain basin with a much drier climate than that in the Hushile basin. The basin is covered by grassland and forest, and the response to rainfall is very fast. There are 16 rain gauges available, but only the mean area values were used in this study. Mean monthly pan evaporation rates and daily discharge data are available. Some selected climatic data on the two basins are given in Table 1.

The optimum parameters for the two models are shown in Table 2 and the observed and calculated hydrographs are shown in Figure 6. Optimum parameters of the HBV model in the Hushile basin were obtained by using the Process Oriented Calibration

TABLE 1. Selected Climatic Data for the Two Test Basins.

Basin and Data Period	Area (km^2)	Precipitation (mm/year)	Runoff (mm/year)	Runoff Coefficient (percent)
Hushile (1980-1985)	492	1740	1030	59
Bird Creek (1956-1962)	2344	960	220	23

TABLE 2. The Optimal Parameters in the Hushile Basin and the Bird Creek Basin.

Hushile Basin				Bird Creek Basin			
X Model		HBV Model		X Model		HBV Model	
Parameter	Values	Parameters	Values	Parameters	Values	Parameters	Values
K	1.11	Fc	230	K	0.95	Fc	200
B	0.27	Lp	0.61	B	0.45	Lp	0.87
C	0.15	β	6.6	C	0.12	β	4.0
WM	120.0			WM	140.0		
UM	18.0			UM	12.0		
LM	50.0			LM	75.0		
SM	8.0	K0	0.44	SM	0.5	K0	0.60
EX	1.0	UZL	20	EX	1.0	UZL	1.5
KG	0.17	K1	0.41	KG	0.04	K1	0.30
KI	0.53	Perc	1.6	KI	0.66	Perc	0
CG	0.935	K4	0.1	CG	0.95	K4	0
CI	0.65	Maxbas	1	CI	0.55	Maxbas	1
CS	0.28			CS	0.15		
LAG	0			LAG	1		

NOTES:

K	=	Ratio of potential evapotranspiration to pan evaporation.
B	=	Parameter in the distribution of tension water capacity.
C	=	Reduction factor for evapotranspiration from deepest soil layer.
WM (UM, LM, DM)	=	Areal mean tension water capacities for the three soil layers (WM=UM+LM+DM.)
SM	=	Areal mean free water storage capacity.
EX	=	Parameter in the distribution of free water storage capacity.
KG	=	Coefficient related to RG, a contribution to ground water storage.
KI	=	Coefficient related to RI, a contribution to interflow storage.
CG	=	Ground water reservoir constant.
CI	=	Interflow reservoir constant.
CS	=	Route parameter of the flow concentration within the subbasin.
LAG	=	The parameter of the flow concentration within the subbasin.
Fc	=	Field capacity.
LP	=	Limit for potential evapotranspiration.
β	=	Exponent parameter in the soil routine.
K0, K1, K4	=	Recession rate parameters.
UZL	=	Threshold between K0 and K1.
Perc	=	Percolation from upper to lower tank.
Maxbas	=	Time of concentration.

Scheme, POC (Harlin, 1991). The POC is a scheme for automatic calibration that attempts to mimic the way an experienced model user would calibrate the HBV model. It uses different criteria for the calibration of the different subroutines in the model. The X model was calibrated by trial and error, as was the HBV model in Bird Creek. This means that the parameters are adjusted manually with the aim of reducing the errors between the calculated and recorded discharge.

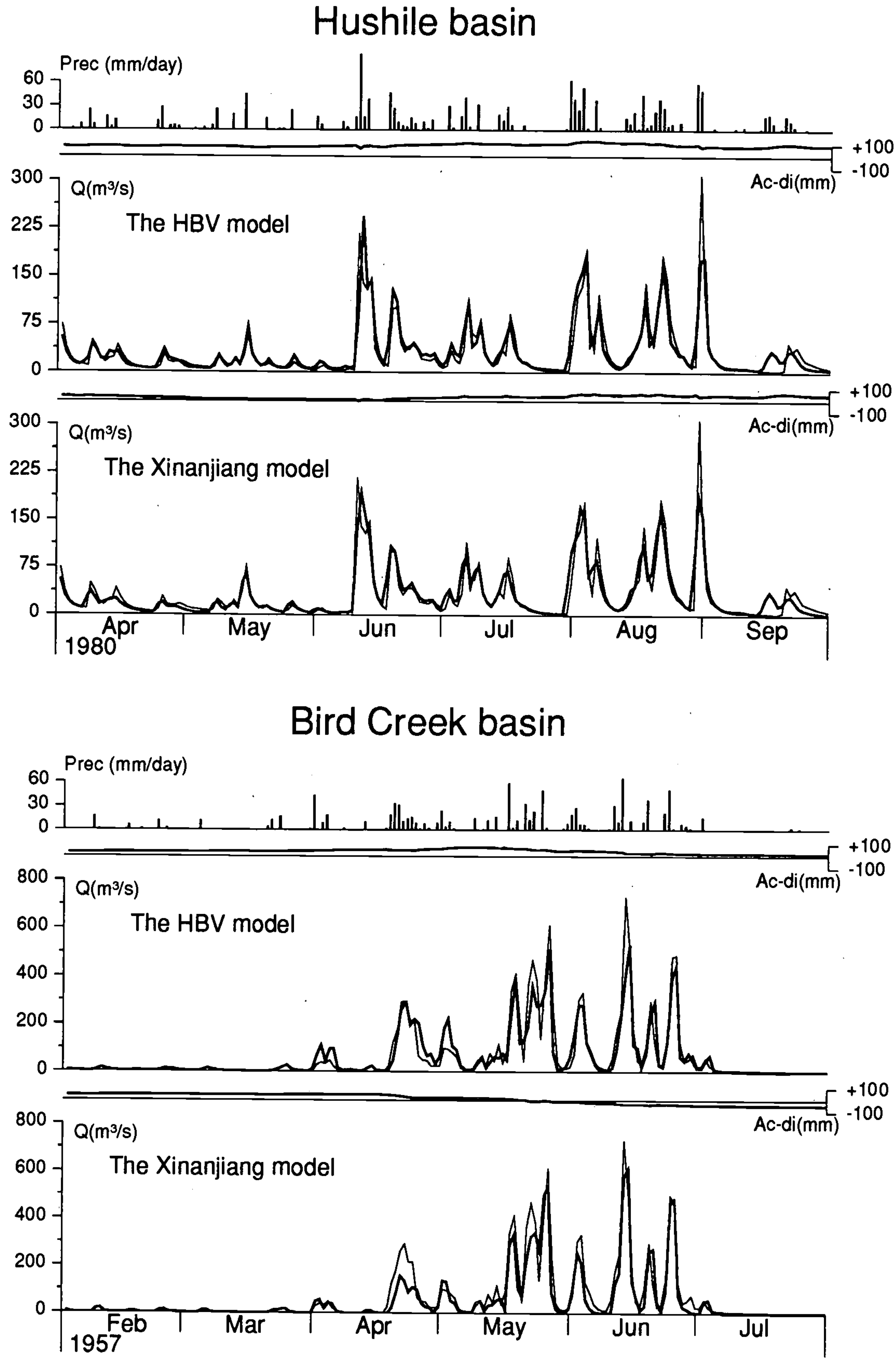

Figure 6. Example of Applications of the HBV and Xinanjiang Models to the Hushile Basin in China and Bird Creek in the U.S.A. Prec = precipitation, Q = computed (thick) and recorded (thin) discharges, Ac-Di = accumulated volume error of runoff.

The efficiency criterion R^2 (Nash and Sutcliffe, 1970) was rather similar for the two basins. Final calibration for the Hushile gave R^2 = 0.86 for both models, and for Bird Creek 0.85 and 0.83 for the X model and the HBV model, respectively. If one model performed poorly for a flood period, the same was usually true for the other model. It was a little easier to achieve good model performances in the Hushile basin than in the Bird Creek basin. The climate of the Bird Creek basin is relatively dry and the rainfall is at times very intense. This situation is more difficult to describe than the more humid situation.

The optimal model parameters were harmonious between the two models and the two basins. A ratio $Rwx = (WM\text{-}WUM)/WUM$ can be defined in the X model, which could be compared with the parameter Lp of the HBV model. In Hushile, Rwx = 0.85 and Lp = 0.61. In Bird Creek, Rwx = 0.91 and Lp = 0.87. The Rwx was larger than Lp in both of the two basins. The Rwx and Lp were larger in Bird Creek than in Hushile. These two parameters were in agreement. The parameter B was larger, and β was smaller in Bird Creek than in Hushile. As Figure 5 shows, they agreed well.

DISCUSSION AND CONCLUSIONS

There are a large number of hydrological models available today. It is, however, not easy to immediately identify the similarities and differences between the different models. Two simple models, the Xinanjiang model and the HBV model, were here compared in more detail. The two models were developed independently of each other, in different parts of the world. The models have both similarities and differences. Both of the two models consist of four routines. The functions of the corresponding routines of the two models are roughly the same. However, there are some fine differences, especially in the soil moisture accounting.

The basic principles of the runoff production of the two models are the same. The runoff coefficient increases with increasing soil moisture but is not directly related to the rainfall intensity. Both models use exponential curves for the relation between rainfall and runoff, and the differences between the two models are small. More important is the difference between the estimation of evaporation in the two models. The three-layer structure of the Xinanjiang model behaves differently than the one-layer HBV model soil routine, at the first rainfall events following a dry period. The model structures of the separation of runoff components of the two models are similar. They both have three kinds of runoff components, and use combinations of linear and quasi-linear tanks. The routing between basins is achieved by use of the Muskingum hydrological routing in both models.

The two models performed rather well in both of the two test basins. It is difficult to see any great difference in quality between the computed hydrographs of the two models. The optimal parameters of the two models in the two basins are in agreement. The merits of the HBV model are the somewhat simpler structure and fewer parameters. The performance of the models was thus not directly related to their complexity. This result is in line with the findings of the WMO model intercomparison (WMO, 1986).

Some observations can be made from the comparison of the two models in the study. Similar results can be obtained with different model structures, and for that matter, also different sets of parameters. We must therefore be cautious when we try to interpret the variables and states of our conceptual models as actual physical values. Furthermore, simulation of the impact of changes in for examples in land use or climate is always uncertain because of the difficulty of choosing one model structure as superior to the others. Any such analysis should be complemented by a sensitivity analysis. The similarity of the results of two independently developed models illustrate the importance of the input data quality and coverage. For operational use, it is probably more worthwhile to try to improve the treatment of input data than to only make more detailed and advanced models.

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