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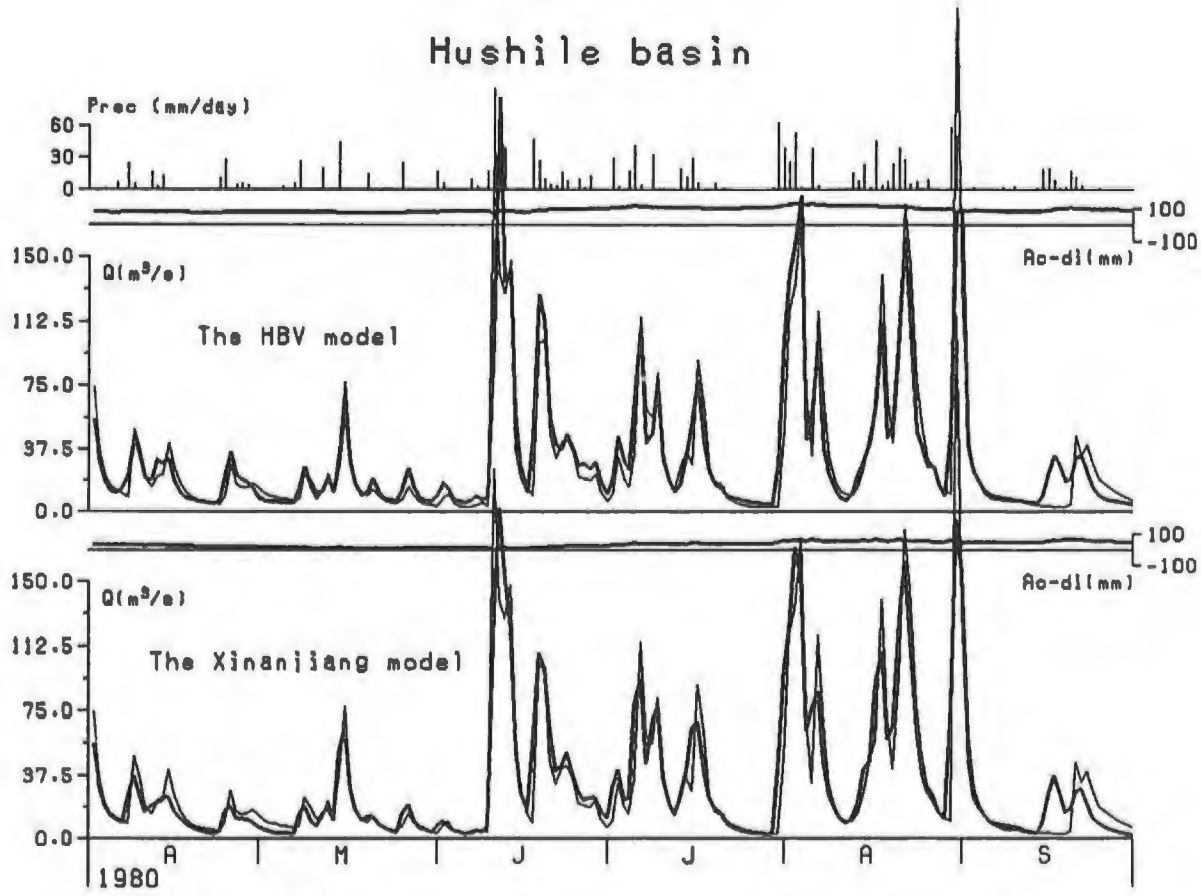

A COMPARATIVE STUDY OF THE HBV MODEL AND DEVELOPMENT OF AN AUTOMATIC CALIBRATION SCHEME

ZHANG Xingnan

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PREFACE

This report contains a comparison between two rainfall-runoff models, namely the Swedish HBV model and the Chinese Xinanjiang model, together with some examples of applications of the two models. It further contains a more detailed study of automatic calibration schemes for the HBV model, as well as the development of a new optimization scheme. The work was carried out by Dr ZHANG Xingnan, on a six month research leave from the Hohai University in Nanjing, China. Dr ZHANGs stay at the Swedish Meteorological and Hydrological Institute was made possible by a grant from the Swedish Institute. Dr ZHANG worked in close cooperation with the staff of the SMHI. The work presented herein was done within the framework of the HBV-2000 project. This project is a revision of the HBV model structure, which has remained relatively unchanged since its development some twenty years ago.

Göran Lindström

ABSTRACT

This report describes the comparison of the HBV model and the Xinanjiang model, the study of the POC (Harlin, 1991), and a new automatic calibration scheme for the HBV model.

The HBV model is compared with the Xinanjiang hydrologic model in the first part. The model structures are compared in four routines except the snow routine of the HBV model. Their integral structures are nearly the same. But, there are some fine discrepancies in some routine, especially in the soil moisture routine. Some parameters of the two models have the same physical definitions. But, they usually have different values in the same basin owing to the discrepancies of the structure. So, we should be careful when a calculated value is used as a real physical value. Both of the two models performed well in two test basins. A merit of the HBV model is the simple structure and the fewer parameters.

The process oriented calibration scheme for the HBV model (POC) is studied in the second part. Tests with the POC were executed in both ideal situations and real situations. Some of the model parameters were insensitive to the efficiency criterion R^2, which makes it difficult to design an automatic calibration scheme. The POC is a successful way of the oriented calibration of the parameters. A problem of the POC is that the optimal parameter values sometimes depend on the initial values and the order of the parameters.

A new automatic calibration scheme for the HBV model (ACSH) is addressed in the third part. A fine modification of the model structure was suggested. As in the POC, the guideline of the ACSH was to simulate the inference of specialists in the manual calibration. Totally nine parameters, except the snow routine, were automatically calibrated in two stages, six steps with the different objective functions. The ACSH performed well in two test basins. The merit of the ACSH is the stable solutions with the different initial values.

PART I

COMPARISON OF THE HBV MODEL AND THE XINANJIANG MODEL

ABSTRACT

The HBV model and the Xinanjiang model are distributed, conceptual and rainfall-runoff models. Usually the basin, in which the HBV model or the Xinanjiang model is applied, is split into several sub-basins. The Xinanjiang model was designed for use in humid and semi-humid regions and there is no routine for the snowmelt runoff. The HBV model has a snow routine used to deal with the snowmelt runoff. The function of the Xinanjiang model is the same as that of the HBV model except the snow routine. The model structures of the two models may be described in four routines, including runoff production, separation of runoff components, flow concentration within a sub-basin, and flow concentration from each sub-basin outlet to total basin outlet. The model structures of the two models are compared in this report. The integral structures of them are almost the same. But, there are some fine discrepancies within the routines, especially in the runoff production routine. The physical significance and physical definitions of some model parameters are analyzed in this report. The physical definitions of some model parameters should be investigated further. Both of the two models were tested in two basins in order to inspect their performance in a practical application. The two models gave similar results, and both performed well in the application.

1. INTRODUCTION

Hydrological models have become more and more popular and play a main part in the realm of water resources and hydrology. They are used not only for flood forecasting but also for many other purposes. There are many hydrological models in the world. Among them, the HBV model and the Xinanjiang model are two successful models. They have all been applied widely and performed well in practice (Bergström, 1992 and Zhao, 1992). The intercomparisons of the models are very useful for the developments of the models. The merits and demerits may be revealed clearly in the intercomparisons. WMO also devoted much importance to this research (see e.g. WMO, 1992). In this part of the report, the two models were compared. The model structures were compared in four aspects, including runoff production, separation of runoff components, flow concentration within a sub-basin, and flow concentration from each sub-basin outlet to total basin outlet. The physical significance of some parameters and realistic ranges of their values are discussed. Finally, the performance of the two models in the two basins is inspected.

2. THE HBV MODEL

The HBV model (Bergström, 1976) is a conceptual hydrological model. It can be used to deal with the snowmelt runoff and also be applied in a basin without snowpack. It can be used as a distributed model by dividing the catchment into sub-basins. Each sub-basin is then divided into zones according to altitude, lake area and vegetation. The model is normally run on daily values of rainfall and air temperature, and daily or monthly estimates of potential evaporation. The model has been applied and tested in many basins all over the world and has a good performance (Bergström, 1992). The model is used not only for flood forecasting but also for some other purposes, such as spillway design floods (Bergström, Lindström and Harlin, 1992), water resources evaluation (Bergström and Carlsson, 1993; Jutman, 1992; Brandt, Jutman and Alexandersson, 1994), etc. There have been many papers giving a detailed description of the model. So, it will not be iterated in this report.

3. THE XINANJIANG MODEL

The Xinanjiang model (referred to as the X model in this report) was developed in 1973 and published in 1980 (Zhao et al., 1980 and Zhao, 1992). It has been applied successfully over a very large area including all of the agricultural, pastoral and forested lands of China except the loess. It has also been tested in some basins of other countries. In China, the X model is used mainly for hydrological forecasting. Recently the model is also 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. Totally there are four routines in the model. Firstly, the runoff R of each sub-basin 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. Secondly, the total runoff R in each sub-basin is separated into three components, RS surface runoff, RI the contribution to interflow, and RG groundwater. To simulate this separation, a tank of free water storage is employed. Thirdly, the different damping effects of the runoff components occurring on the hillside of the basin are simulated by the linear reservoirs. To simulate the flow concentration in the channel network within the sub-basin, the convolution of empirical unit hydrograph or the "lag and route" method with parameters L and CS is adopted. The later is, recently, adopted much more frequently than the former since it has two parameters only and since calibration of the parameters is easy. Finally, the flow concentration from each sub-basin outlet to total basin outlet is achieved by applying the Muskingum method.

4. THE STRUCTURE OF THE HBV MODEL AND THE X MODEL

The integral structures of the HBV model and the X model are similar except for the snow routine of the HBV model. The snow routine of the HBV model will be out of use if the model is applied in a watershed without snowpack. The comparison of the model structures mentioned in this report means that without the snow routine.

4.1. Runoff Production

The runoff is produced in the soil aeration zone. There is a soil moisture balance in the zone. The measured precipitation minus 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.

4.1.1. Evaporation

The evaporation mechanism of the X model is a three-layer soil moisture model, i.e. the total tension water capacity WM in soil aeration zone is divided into three layers, WUM, WLM and WDM. There are four parameters K, WUM, WLM and C for evaporation calculation. The parameter WDM equals to WM minus WUM and WLM. WM is a parameter for runoff production. The actual evaporation E in a basin relates to potential evaporation and soil moisture storage W. An observed pan evaporation rate EM is usually available. The actual potential evaporation rate EK of a basin equals $K*EM$. The parameter K depends on the type of the pan and the difference between the elevations of the pan and the basin. The evaporation process of the X model is illustrated in Fig. 1-1.

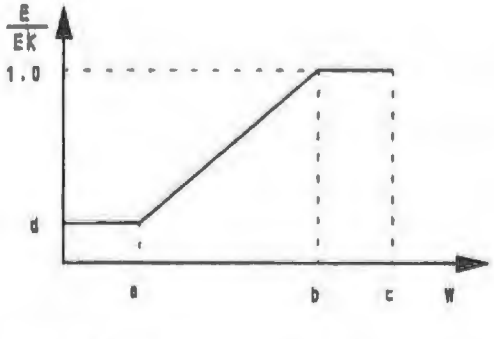

Fig.1-1 The evaporation mechanism of the X model
*a=WDM+C*WLM, c=WM*
b=WDM+WLM, d=C

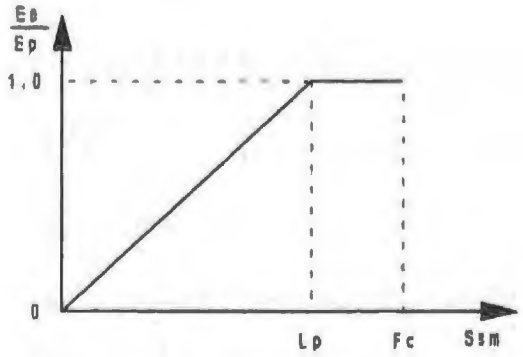

Fig.1-2 The evaporation mechanism of the HBV model

Firstly, evaporation occurs from the upper layer (referred to as EU) by the potential evaporation rate, corresponding to the range between b and c in Fig. 1-1,

$$EU=EK=K*EM \qquad (1-1)$$

When the actual computed soil moisture storage WU of the upper layer is exhausted, any remaining EK is applied on the lower layer (referred to as EL),

$$EL=(EK-EU)*WL/WLM \qquad (1-2)$$

where WL is the computed soil moisture storage of the lower layer. When WL is less then WLM times C, let the $EL=C*(EK-EU)$. When WL is exhausted, the evaporation occurs from the deep layer.

After accounting for the runoff and the actual evaporation, the remaining precipitation (RP) will flow into the soil aeration zone if the rainfall exceeds the potential evaporation rate. In the X model, the upper layer is replenished first. When WU reaches up to its capacity WUM, the RP will flow into the lower layer, and then the deep layer.

The evaporation mechanism of the HBV model is shown in Fig. 1-2. It can be expressed as

$$\begin{aligned} Ea&=Ep && Ssm\geq Lp \\ Ea&=Ep*Ssm/Lp && Ssm<Lp \end{aligned} \qquad (1-3)$$

where: Ep=potential evaporation,
Ea=actual evaporation,
Ssm=actual computed soil moisture storage, and
Lp=limit for potential evaporation.

The precipitation minus the runoff and the actual evaporation will flow into the soil aeration zone similarly to the X model if the rainfall exceeds the potential evaporation rate.

The evaporation mechanisms of the two models are similar, but not exactly the same. The evaporation rate will tend to zero when the soil tension moisture tends to zero in the HBV model. But, it will tend to the potential evaporation rate times a constant in the X model. This discrepancy will be distinct if the basin is located in a relatively arid climate region. In this kind of basins, a relatively large Fc of the HBV model could be derived, possibly in order to enlarge the calculated evaporation to agree the actural basin evaporation.

Another main difference between the two models is the replenishment of soil moisture. In the X model, the RP replenishes into the upper layer firstly, and eventually this part of the moisture will evaporate back to atmosphere at the potential evaporation rate. In the HBV model, there is no such soil moisture layers. In the HBV model, it is like that the RP flows into the lower layer first in the X model if the soil moisture has not reached its capacity. In this case, the evaporation value of the X model will be larger than that of the HBV model. In Table 1-1, an example is given, where there are a series of potential evaporation values, a rainfall at the first day and the same initial soil moisture for both the X model and the HBV model. The parameters of the X model are WUM=15, WLM=80 and WDM=55. The parameters of the HBV model are Fc=150 and Lp=135. We assume that the runoff produced at the first day is 10 mm for both of the

two models. The calculations of actual evaporation E are shown in Table 1-1.

Table 1-1 The example of evaporation calculation

date	P	EK	R	X					HBV	
				WU	WL	WD	W	E	Ssm	E
0				0	20	55	75		75	
1	25	2	10	13	20	55	88	2	88.9	1.1
2		5		8	20	55	83	5	85.61	3.29
3		5		3	20	55	78	5	82.44	3.17

In this example, the soil moisture evaporates in potential evaporation rate in the X model. But, in the HBV model, the evaporation depends on Lp/Fc and is less than potential. Perhaps this is one of the reasons why Fc is usually larger than WM. The computed evaporation value will increase with an increase of Fc in the HBV model.

There is a old and interesting problem in this element of the models. The parameters Fc and WM have the same physical significance in the models. They express the tension soil moisture and can both give good model performance individually. They also have the same physical definitions, i.e. their values are equal to the maximum soil moisture which can be evaporated back into atmosphere. But, their values are not usually the same. So, we should be very careful when the computed soil moisture of a model is adopted as a real physical value. We prefer to use 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.

4.1.2 Runoff

The movement of soil moisture in the soil aeration zone is the key of the runoff production. The runoff production relates to the amount of soil moisture in the zone. So, the relationships of runoff and soil moisture were established to deal with the runoff production in most of hydrological model, including the X model and the HBV model.

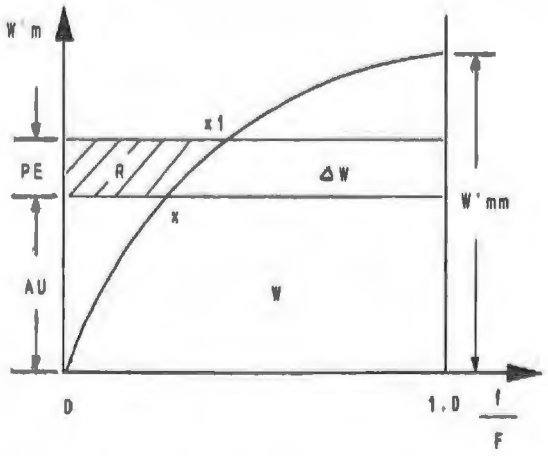

Fig. 1-3 The distribution of tension water capacity in the sub-basin

In the X model, runoff production occurs only on the repletion of the tension water storage at a point in the basin. To provide for a non-uniform distribution of tension water capacity, a curve (Fig. 1-3) is introduced. These two points are the essential hypotheses for the runoff pro-

duction of the X model.

In Fig. 1-3, F is the total area of a sub-basin and f represents the pervious area of the sub-basin. The tension water capacity in the pervious area is less then or equals to the value of the ordinate $W'm$. The $W'm$ varies from zero to a maximal value $W'mm$ according to the relationship,

$$(1-\frac{f}{F}) = (1-\frac{W'm}{W'mm})^{B} \qquad (1-4)$$

where B and $W'mm$ are parameters.

The areal mean tension water capacity WM constitutes an alternative parameter to the $W'mm$. They are related through the parameter B. From Equ. (1-4) and Fig. 1-3, by integration, it is easy to show that

$$WM = \int_0^1 W'mm \; d(\frac{f}{F}) = W'mm/(1+B) \qquad (1-5)$$

and AU to the actual mean tension water storage W is shown as

$$W = \int_0^{AU} (1-\frac{f}{F}) \, dW'm \qquad (1-6)$$

Substituting the $(1-f/F)$ of Equ.(1-6) with Equ. (1-4) and then integrating Equ. (1-6), we can get Equ. (1-7),

$$AU = W'mm \, [1-(1-\frac{W}{WM})^{\frac{1}{1+B}}] \qquad (1-7)$$

The state of the catchment, at any time, is assumed to be represented by a point x on the curve of Fig. 1-3. The area of the right and below side of the point x is directly proportional to W. This assumption implies that each point in the sub-basin is either at capacity tension (point to the left side of x) or at a constant tension (point to the right side of x).

When rainfall exceeds simultaneous evaporation, the ordinate of Fig. 1-3 is increased by the excess, x moves upwards to x_1 along the curve and the runoff is generated in direct proportion to the shaded area shown to the left and above side of the point x in Fig. 1-3. The PE represents the rainfall minus the simultaneous evaporation. The runoff calculation can be presented as the following by integration according to Fig. 1-3.

$$\int_0^R dR = \int_0^{PE} \frac{f}{F} \, dW'm \qquad (1-8)$$

consequently,

$$
\begin{aligned}
&R = PE - (WM - W) && PE + AU \geq W'mm \\
&R = PE - (WM - W) + WM\left[1 - \frac{PE + AU}{W'mm}\right]^{1+B} && PE + AU < W'mm
\end{aligned}
\qquad (1\text{-}9)
$$

Equ. (1-9) is an algebraic equation, not a differential equation. So, we need not to use a difference scheme to calculate the runoff.

According to Equ. (1-8), the coefficient of runoff dR/dP can be derived as,

$$
\begin{aligned}
&\frac{dR}{dP} = \frac{f}{F} = 1 - \left(1 - \frac{W}{WM}\right)^{\frac{B}{1+B}} && W < WM \\
&\frac{dR}{dP} = 1 && W \geq WM
\end{aligned}
\qquad (1\text{-}10)
$$

Equ. (1-10) means that the coefficient of runoff is a function of W/WM.

The runoff production mechanism of the HBV model is much simpler than that of the X model. It is assumed that there is a distribution of soil types which can be described by the relationship (Bergström, 1976),

$$
\begin{aligned}
&\frac{dQ}{dP} = \left(\frac{Ssm}{Fc}\right)^{\beta} && Ssm < Fc \\
&\frac{dQ}{dP} = 1 && Ssm \geq Fc
\end{aligned}
\qquad (1\text{-}11)
$$

where Q means runoff and is equivalent to R of the X model. The Ssm means actual soil moisture storage and is epuivalent to W of the X model. The Fc is a parameter, which means the storage capacity of soil moisture, and is equivalent to WM of the X model. The β is a free parameter and its function is similar to that of B of the X model.

Comparing the two mechanisms, there are four common grounds:

a. The relationship between the coefficient of runoff and soil moisture is represented as an exponential function;
b. The runoff production is independent of the rainfall intensity;
c. All rainfall contributes to the runoff when $W = WM$ in the X model or $Ssm = Fc$ in the HBV model;
d. The coefficient of runoff tends to zero when the soil tension water storage tends to zero.

The developments of the coefficient of runoff of the two models with the soil moisture are shown in Fig. 1-4.

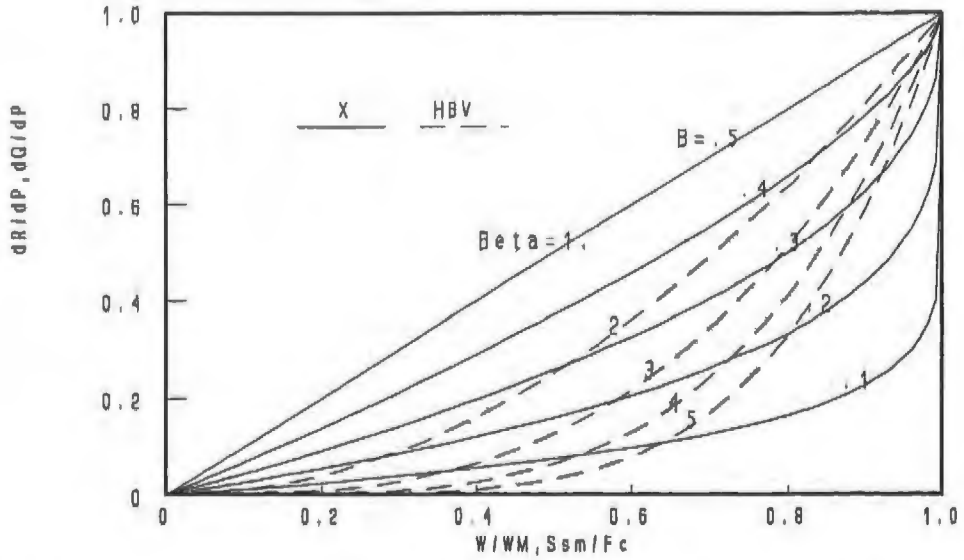

Fig.1-4 The development of the coefficient of runoff with soil moisture

where the solid line represents that of the X model and dotted line the HBV model. We may get an idea from Fig. 1-4 and their common grounds that there is no essential difference between the two models. But, they are not exactly the same. It is difficult to say which one is closer to the actual state of a natural basin.

4.2. Separation of runoff components

In the X model, the total runoff R is separated into three components, RS surface runoff, RI interflow and RG groundwater. To model this separation, the concepts of free water storage S and free water storage capacity SM are used. The latter is assumed to be distributed over f (cf. Fig. 1-3) in a parabolic manner (Fig. 1-5). The variable f is the portion of the subbasin, in which runoff is being currently produced.

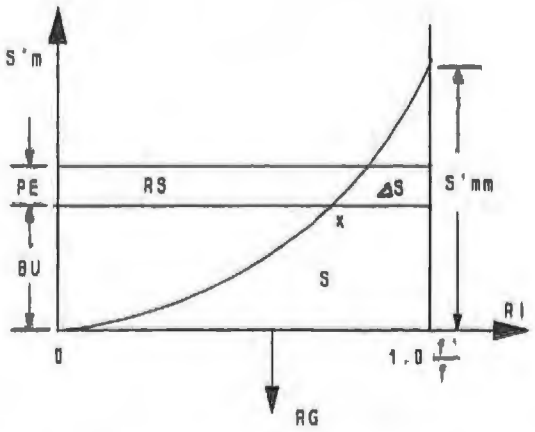

Fig.1-5 The structure of separation of runoff components of the X model

The curve is represented as follow,

$$(1-\frac{f'}{f}) = (1-\frac{S'm}{S'mm})^{Ex} \qquad (1\text{-}12)$$

where f' is the portion of f, in which the free water storage capacity is less than or equal to $S'm$. The $S'mm$ is the maximum value of $S'm$ and means that the maximum free

water storage capacity of the point in the sub-basin. The Ex is a free parameter and controls the shape of the curve.

The architecture of this element is the same as that used to model the tension water. It is assumed that the current state of free water storage in f can be represented by a point x (ordinate BU on the parabola of Fig. 1-5) implying that the free water storage in the portion of the left side of point x is at capacity storage and that of the right side of point x is at a constant, below capacity level. Therefore, we get the relations,

$$S'mm = (1+Ex)\,SM \qquad (1-13)$$

The remainder of R becomes an addition ΔS to the free water storage S, which in turn contributes interflow RI laterally and groundwater RG vertically, according to the relations,

$$BU = S'mm\left[1-\left(1-\frac{S}{SM}\right)^{\frac{1}{1+Ex}}\right] \qquad (1-14)$$

$$\begin{aligned} RS &= \left\{PE-SM+S+SM\left[1-\frac{PE+BU}{S'mm}\right]^{1+Ex}\right\}\frac{f'}{f} && PE+BU<S'mm \\ RS &= (PE+S-SM)\,\frac{f'}{f} && PE+BU\geq S'mm \end{aligned} \qquad (1-15)$$

$$\begin{aligned} RI &= S*KI*\frac{f}{F} \\ RG &= S*KG*\frac{f}{F} \end{aligned} \qquad (1-16)$$

where KI and KG are parameters.

In the HBV model, there is a similar architecture, referred to as the upper tank in Fig. 1-6.

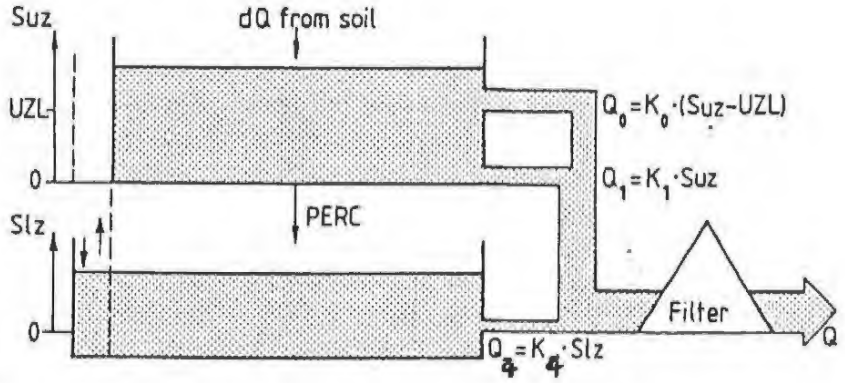

Fig.1-6 The runoff-responce function of the HBV model

where K_0, K_1 and $Perc$ are free parameters. The UZL is a threshold parameter of water storage. The storage Suz of the upper tank represents the total runoff derived from the

runoff production routine.

There are also three kinds of runoff components Q_0, Q_1 and Q_4. But, the storage Suz is distributed evenly in the basin.

When Ex=0, K_0=1 , SM=UZL and K_1=$K1$, the two models are nearly the same.

In the X model, the value of Ex is usually around 1 and there will be surface runoff as long as there is runoff. In the HBV model, there will be a flow Q_0 when the storage Suz exceeds the threshold parameter UZL. Since $k_0 \leq 1$ in the HBV model, there will be a damping action on Q_0 although this action is not so great. In the X model, there is not this kind of damping action on surface runoff. The $Perc$ is a constant in the HBV model. It means how much water, which will percolate into the lower tank as Q_4, is not related to the storage Suz of the upper tank at that moment. In the X model, the groundwater is directly proportional to the storage S at any moment.

The runoff components of the two models are not exactly the same when the two models are applied in the same basins, although their structures are similar and there are the same three kinds of runoff components. But, both of them can perform well in practice. So, we should be prudent when some kinds of runoff components are adopted as actual physical values, such as using calculated Rg or Q_4 to estimate the groundwater resources of a basin. Maybe this kind of runoff separation is only a method used to deal with the non-linear damping of the runoff concentration on the hillslope.

4.3. Flow concentration within a sub-basin

The flow concentration within a sub-basin can be split into two stages, on hillslope and in channel network.

Firstly, the runoff comes down along the hillslope and forms the inflow to the channel system within the sub-basin. The performances of the different runoff components are not the same in this stage. The duration of the concentration of surface runoff is shorter than that of interflow, and similarly the duration of interflow is shorter than that of groundwater. There have been the damping actions in the runoff separation routine in both of the two models. But, these damping actions are not sufficient enough, especially for groundwater.

In the X model, it is assumed that we can neglect the damping to surface runoff RS, i.e. the RS passes through the hillslope unmodified to the channel system as TS. The interflow RI and the groundwater RG are routed by linear reservoirs to the channel system as TI and TG individually. The outflows TI and TG from these reservoirs are determined by

$$\begin{aligned} TI(t) &= TI(t-1)*CI+RI(t)*(1-CI) \\ TG(t) &= TG(t-1)*CG+RG(t)*(1-CG) \end{aligned} \qquad (1\text{-}17)$$

where CI and CG are free parameters. The parameter CI is much smaller than CG.

Usually the damping action on RI is small in a natural basin and can sometimes be neglected. The TI and TG are added to TS to become the total inflow T of the channel network within a sub-basin.

In the HBV model, it is considered that the damping actions on Q_0 and Q_1 are enough in the runoff separation routine. Only one linear reservoir, referred to as the lower tank in Fig. 1-6, is employed for groundwater. The calculation formula is as follow,

$$Q_4 = K_4 * Slz \qquad (1\text{-}18)$$

where K_4 is a free parameter and Slz is the water storage in the lower tank. Equ. (1-18) is the same as Equ. (1-17), which can be proven simply. We rewrite Equ. (1-18) into Equ. (1-19) using t to express the time step.

$$Q_4(t) = K_4 * Slz(t) \qquad (1\text{-}19)$$

Using a backward difference scheme, the water balance equation of the lower tank is as follows,

$$Slz(t) = Slz(t-1) + Rp(t) - Q_4(t-1) \qquad (1\text{-}20)$$

where $Rp(t)$ expresses the runoff, which percolates from the upper tank to the lower tank according to the parameter $Perc$ within the time interval of t-1 to t. Substituting the Slz with Equ. (1-19), we can get the Equ. (1-21).

$$Q_4(t) = (1-k_4) * Q_4(t-1) + K_4 * Rp(t) \qquad (1\text{-}21)$$

Equ. (1-21) is an alternative fashion of Equ. (1-19) and is the same as Equ. (1-17). The parameter CG in the X model should be equal to 1-K_4 in the same basin according to their physical significance.

Secondly, the runoff concentrates in the channel system within the sub-basin, and then forms the outflow at the outlet of the sub-basin. In this stage, all the runoff components have the same performances.

In the X model, the total inflow T of the channel network is convoluted in an empirical unit hydrograph or in the "lag and route" method with parameters L and CS to produce the sub-basin outflow Q. The empirical unit hydrograph is well known. The "lag and route" method means that the total inflow T is regulated by a linear reservoir firstly and then by a linear channel. The parameter CS acts as the linear reservoir and the fashion of the calculation formula is the same as Equ.(1-17), substituting TI with Q, RI with T and CI with CS. The parameter L acts as a linear channel, i.e. the hydrograph is moved backwards L time steps without affecting the shape. In the HBV model, a simple routing transformation is adopted in order to account for this damping. It is a triangular distribution of weights with the base length $MAXBAS$, i.e. an unit hydrograph. There is no essential difference between the two models in this routine.

4.4. Flow concentration from each sub-basin outlet to total basin outlet

The Muskingum method is adopted in both of the two models. So, there is no difference between the two models.

5. THE APLLICATIONS OF THE HBV MODEL AND THE X MODEL IN TWO BASINS

The best 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 lot of basins. Now their performances are compared in two basins, Hushile, a Chinese basin and Bird Creek, a basin in United States.

The Hushile watershed is located in the middle eastern region of P. R. of China and covers an area of about 492 km^2. It is a rolling terrain basin, is located in a humid region. The mean annual precipitation (1980-1985) was about 1743 mm and the mean annual runoff (1980-1985) was about 1028 mm. The coefficient of runoff was thus 0.59. There is a good vegetative cover all over the basin and no snow. There are six rain-gauges, and one evaporation observation station. Daily data of discharge at the outlet of basin are available.

The Bird Creek basin is located in the central part of the United States and covers an area of about 2344 km^2. It is a rolling terrain basin with a moderately humid climate. There is no snow. The mean annual precipitation (1956-1962) was about 964 mm and mean annual runoff (1956-1962) was about 221 mm. The coefficient of runoff was thus 0.23. The basin is covered by grassland and forest. There are fast-responding discharges at the outlet of the basin. There are sixteen rain-gauges, but only the mean area values were here adopted. Mean monthly pan evaporation rates and daily discharge data are available. The models were run in seven years totally (1956-1962). This basin was selected as one of the test basins for the Simulated Realtime Intercomparison of Hydrological Models (WMO, 1992).

The HBV model and the X model were tested in both of the two basins. The optimal parameters are shown in Table 1-2. The observed and calculated hydrographs are shown in Fig. 1-7 and Fig.1-8. The optimum parameters of the HBV model in the Hushile basin were obtained by using the Process Oriented Calibration Scheme (POC) (Harlin, 1991).

Both of the two models performed well in the tests. There was no remarkable difference between the two models in neither the efficiency criterion R^2 (Nash and Sutcliffe, 1970) nor the calculated hydrographs. If one model performed poorly for a flood, the same was true for the another model. The model performance was much better in the Hushile basin than in the Bird Creek basin.

Table 1-2 The optimal parameters

Hushile basin				Bird Creek basin			
X model		HBV model		X model		HBV model	
Par.	Values	Par.	Values	Par.	Values	Par.	Values
K	1.11	Fc	229.7	K	0.95	Fc	200.00
B	0.27	Lp	0.608	B	0.45	Lp	0.87
C	0.15	β	6.59	C	0.12	β	4.0
WM	120.0			WM	140.0		
WUM	18.0			WUM	12.0		
WLM	50.0			WLM	75.0		
SM	8.0	K0	0.441	SM	0.5	K0	0.60
EX	1.0	UZL	20.00	EX	1.0	UZL	1.5
KG	0.17	K1	0.413	KG	0.04	K1	0.30
KI	0.53	Perc	1.588	KI	0.66	Perc	0.0
CG	0.935	K4	0.0997	CG	0.95	K4	0.05
CI	0.65	Maxbas	1	CI	0.55	Maxbas	1
CS	0.28			CS	0.15		
LAG	0			LAG	1		

The climate of the Bird Creek basin is relatively dry. There will not be any runoff if the soil aeration zone is dry and the rainfall is some ten or twenty millimeters. But, in both of the two models, there will always be runoff from any rainfall as long as the soil moisture above zero. The fast-responding discharge, the lower coefficient of runoff and the small groundwater storage are all related to the intensity of rainfall. These factors indicate that the mechanisms of runoff production of both the two models may be not a sufficient description of the Bird Creek basin.

The optimal model parameters were harmonious between the two models and the two basins. We can define a ratio $Rwx=(WM-WUM)/WUM$ 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 were larger than Lp in both of the two basins. The Rwx and Lp were larger in Bird Creek than in Hushile. They were harmonious. The parameter B was larger, and β was smaller in Bird Creek than in Hushile. On the basis of Fig. 1-5, they were harmonious. The parameters SM and SZL were all very small in Bird Creek because there is only a little groundwater.

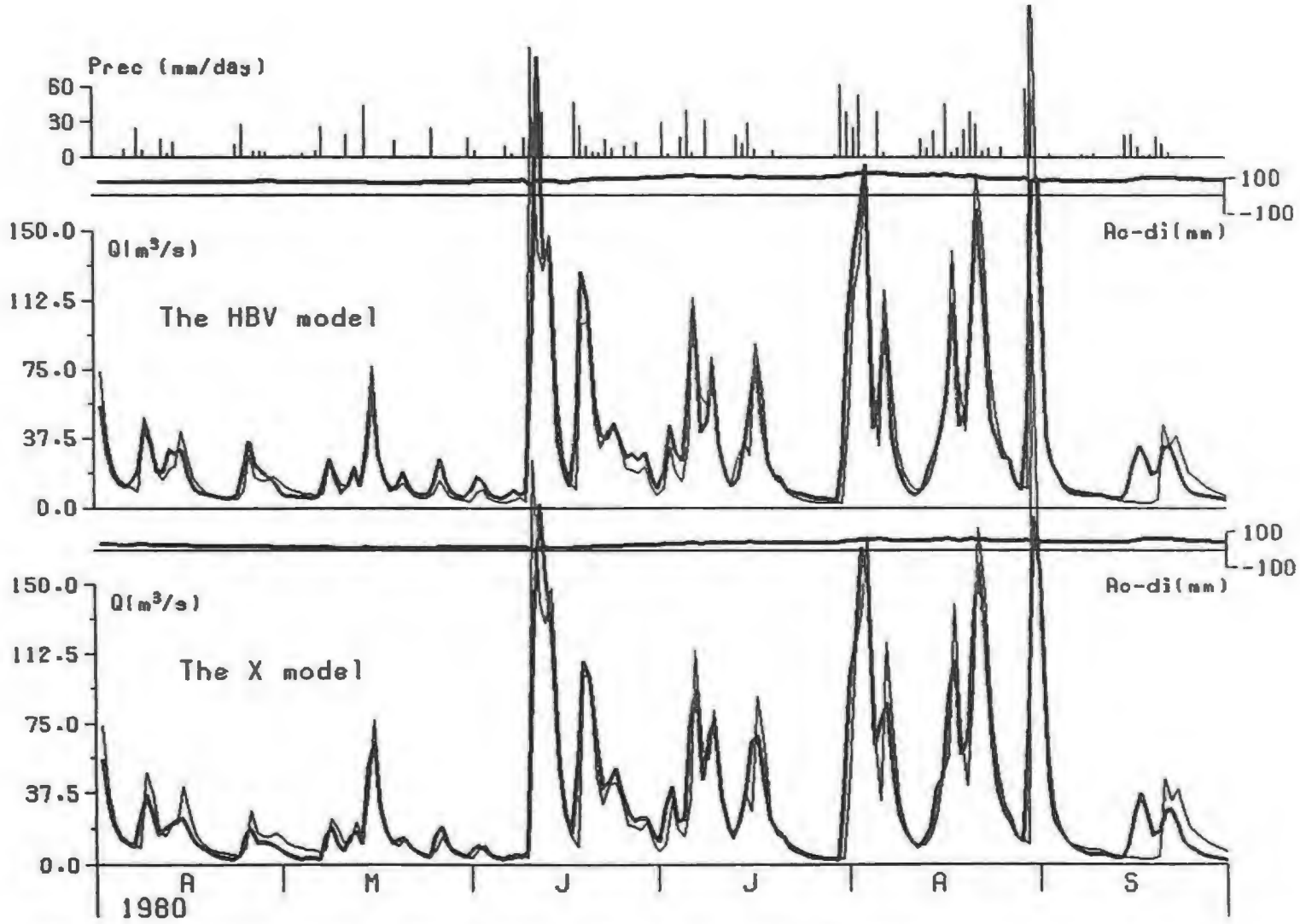

Fig. 1-7 The computed (thick lines) and observed (thin lines) hydrographs for the Hushile basin. Above: the result of the HBV model, Below: the result of the Xinanjiang model.

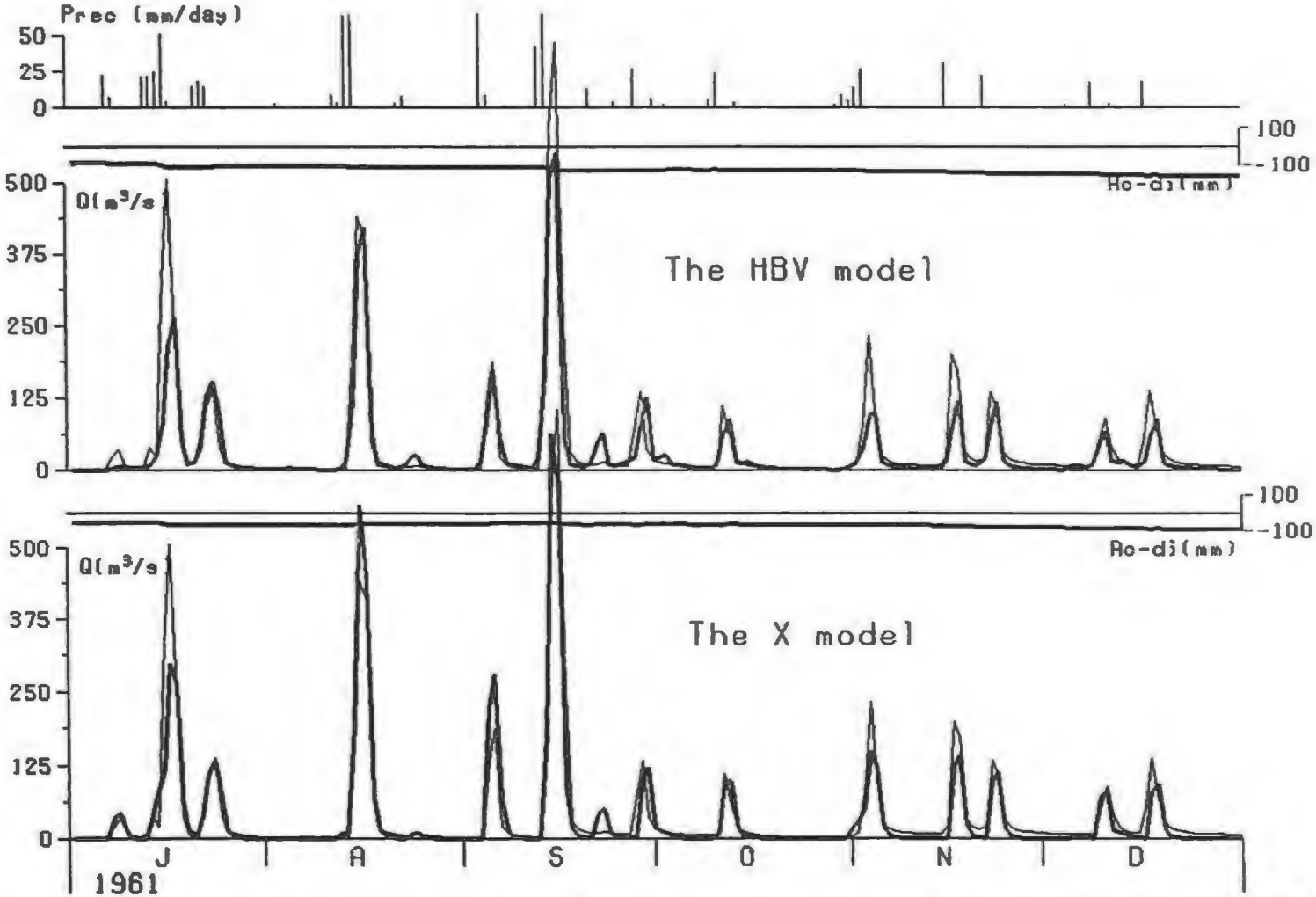

Fig. 1-8 The computed (thick lines) and observed (thin lines) hydrographs for the Bird Creek basin. Above: the result of the HBV model, Below: the result of the Xinanjiang model.

6. CONCLUSIONS

The integral structures of the two models are almost the same. They can both be described by four routines. The functions of the corresponding routines of the two models are the same. But, there are some fine discrepancies within the routines, especially in the soil moisture routine. We should be prudent when the computed soil moisture of a model is adopted as a real physical value. The basic principles of the runoff production of the two models are the same. The runoff is directly proportional to the soil moisture. But, the types of the curve family of the relationship between the coefficient of runoff and the soil moisture are not exactly the same, although they are all exponential curves. The model structures of the separation of runoff components of the two models are similar, but not exactly the same, although they both have three kinds of runoff components. The merits of the HBV model are the simple structure and the few parameters. The two models performed well in both of the two test basins. It is difficult to see any remarkable difference between the modelled hydrographs of the two models. The optimal parameters of the two test models in the two basins are harmonious.

PART II

STUDY OF THE PROCESS ORIENTED CALIBRATION SCHEME FOR THE HBV MODEL

ABSTRACT

The automatic calibration of hydrological model parameters is an important but difficult problem in the application of the models. Many model designers have developed or are developing automatic calibration schemes for their models. It is, however, not easy to make a scheme efficient enough to be used in practical applications. The process oriented calibration scheme (POC) for the HBV hydrological model was developed by Harlin (1991). Totally twelve parameters are calibrated in two steps, the initial parameter estimates and the auto-optimization of the parameters. The parameters are calibrated individually in an iteration loop starting with the snow routine, over the soil routine and finally the runoff-response function. This part of the report is aimed at the study of the characters of the POC. The different parameter sets, including different number and different order of the parameters, were inspected in the POC, except the snow routine. The automatic calibration was tested with different initial values. The tests were carried out in the ideal situation and also in the real situation of a basin. The POC is an efficient scheme for fine-tuning the model parameters. But, some problems should be further discussed, such as the dependence of the optimal values of the parameters no different initial values and different parameter orders.

1. INTRODUCTION

Over the past three decades, there have been great developments in hydrological models. The hydrological models have been used as the main tool for flood forecasting, and also for other purposes. The most important but difficult problem of applying the hydrological models is the calibration of the model parameters. The calibration requires profound knowledge about the model structure and parameters. Usually, it is completed by skilled hydrological experts. The popularization of the hydrological models will be restricted due to the difficult calibration of the parameters. On the other hand, there will be different manual optimal values with the different hydrologists even though they are all experts in parameter calibration. This will reduce the confidence in manual calibration. So, most model designers want to develop the automatic calibration schemes for their models, such as Bergström (1976), Zhang (1988), Sugawara (1979), Brazil (1989), Sorooshian and Dracup (1980), Sorooshian and Gupta (1983), Gupta and Sorooshian (1985), and so on. It is, however, very difficult to develop a successful scheme, although most of the developers claimed that their schemes perform well in practical applications.

The process oriented calibration scheme (POC) for the HBV model was developed by Harlin (1991). The philosophy of the POC was to utilize the physical representation of

the model components and the experience from manual calibrations. This was done by splitting the calibration period into sub-periods, i.e. snow melt, rain flood, flood, and base flow sub-periods. In this manner the parameters are only evaluated over the sub-periods where they are active. Different criterions were used for different parameters in the POC. The different sub-periods were compiled by combining the observed temperature and the observed discharge.

In the POC, twelve parameters were calibrated in two steps. Firstly, initial values of the parameters were made from recession analysis of the observed discharge. From the duration curve of the observed discharge, two characteristic discharges *Qh* and *Qb* corresponding to two turning points on the curve were derived. The initial values of the parameters K_0, K_1, K_4, *UZL* and *Perc* were guessed on the basis of *Qh* and *Qb*. The *Maxbas* was initially set to one day, and the remaining six parameters were initially set to the middle of their respective ranges found by experience from a large number of manual calibrations of Swedish basins. Secondly, an iteration loop was performed over the whole model. The parameters were calibrated one at a time in a set order starting with the snow routine, over the soil routine and finally the runoff-response function. This manner means that all calibrated parameters were set in a order, one parameter at a time. When the parameters were all optimized, the second loop began in the same manner as the first loop. So, the sets with different order are the different parameter sets. The calibrated parameters in a set can include all of the model parameters, or a part of them. The iteration loops continue until the criterion R^2 for the whole calibration period stabilizes.

The auto-optimization method adopted in the scheme is the Parabolic Interpolation and Brent's Method (Press et al., 1992). It is specially designed for one-dimension problems. There is a convergence index, *Tol* in the method. In the POC, two convergence indexes, *Tol1* and *Tol2* were defined. *Tol1* was used for the first loop and *Tol2* for the following loops. These two indexes should be defined individually for each calibrated parameter in the POC.

This part of the report is aimed at studying the characters of the POC. Different sets of the calibrated parameters were made, which include different numbers and different orders of the parameters. Each set was tested individually with different initial values. The initial values were selected arbitrarily. The snow routine was not needed in the Hushile basin, and the parameters of this routine were not investigated in this report. The sub-period splitting will be not so important when there is no snowmelt runoff. So, the calibration period was not split into sub-periods in this report. All the parameters were calibrated over the whole period. The objective functions for the different parameters suggested by Harlin (1991) were adopted. The objective function for *Maxbas* was R^2, expressed as

$$R^2 = 1 - \frac{\sum_{j=1}^{n} (Q_o(j) - Q_o(j))^2}{\sum_{j=1}^{n} (Q_o(j) - Q_{om})^2} \qquad (2\text{-}1)$$

where n = number of timesteps,

$Q_c(j)$ = computed discharge,
$Q_o(j)$ = observed discharge,

and

$$Q_{om} = \frac{1}{n} \sum_{j=1}^{n} Q_o(j) \quad .$$

The objective function for all other parameters was MSE, expressed as

$$MSE = \frac{1}{n} \sum_{j=1}^{n} (Q_c(j) - Q_o(j))^2 \quad . \qquad (2\text{-}2)$$

The criterion period, in which the modelling errors were counted in the objective function, started on the first of August of the first year in the following tests in order to avoid the effect of unsuitable initial values.

In this report, all the tests were carried out in the Hushile basin (cf. Part I). The calibration period is totally six years from 1980 to 1985. The tests were executed in two situations, the ideal situation and the real situation.

2. TESTS IN THE IDEAL SITUATION

The ideal situation here means that a set of parameter values was defined in advance and the computed discharge with this set of parameters was adopted as the output of the basin. These fixed values of the parameters are referred to as their true values in the ideal situation.

The R^2 will equal to 1.0 if we run the model with the true values in the ideal situation, which means that there is an only solution of model parameters in the basin. In this case, there are no data problems, i.e. there is no interference caused by unreliable observed data.

In this report, the true values of the parameters of the HBV model in the Hushile basin were defined as in Table 2-1.

Table 2-1. The true values of the parameters

Maxbas	*Fc*	*Lp*	β	K_1	K_0	*UZL*	*Perc*	K_4
1.0	200.0	0.8	2.0	0.2	0.4	20.0	1.0	0.02

Test 1: The sensitivity of some parameters to the objective function R^2 was inspected in the test. In Table 2-2, when one parameter was altered, all other parameters were kept at their true values.

Table 2-2(1) The sensitivities of some parameters. $pK_4=K_4/0.02$, $pK_0=K_0/0.4$, $pU=UZL/20$

K_4	pK_4	R^2	K_0	pK_0	R^2	UZL	pU	R^2
.010	.50	.9996630	.25	0.625	.9761529	10	0.5	.9847611
.015	.75	.9999372	.30	0.750	.9897958	14	0.7	.9945486
.020	1.00	1.000000	.35	0.875	.9975523	16	0.8	.9975803
.025	1.25	.9999624	.40	1.000	1.000000	20	1.0	1.000000
.030	1.50	.9998828	.45	1.125	.9977462	24	1.2	.9977907
.035	1.75	.9997614	.50	1.250	.9913622	26	1.3	.9954053
.040	2.00	.9996425	.55	1.375	.9813434	30	1.5	.9884622

Table 2-2(2) The sensitivities of some parameters. $pFc=Fc/200$, $pLp=Lp/0.8$, $p\beta=\beta/2.0$

Fc	pFc	R^2	Lp	pLp	R^2	β	pβ	R^2
100	0.500	.980605	0.4	0.500	.991908	1.0	0.50	.991661
150	0.750	.996595	0.5	0.625	.992654	1.5	0.75	.998698
175	0.875	.999204	0.6	0.750	.995074	2.0	1.00	1.000000
200	1.000	1.000000	0.7	0.875	.998272	2.5	1.25	.999308
225	1.125	.999481	0.8	1.000	1.000000	3.0	1.50	.997760
250	1.250	.998175	0.9	1.125	.997754	3.5	1.75	.995763
300	1.500	.994159	1.0	1.250	.991331	4.0	2.00	.993492

According to Table 2-2, some parameters are more sensitive than others. The parameter K_0 is the most sensitive one in Table 2-2(1) and Lp in Table 2-2(2).

It is clear in Table 2-2 that the alteration ranges of the parameters were still considerably large even if the corresponding R^2 were not less than 0.99, i.e. the alterations of R^2 with the alterations of the parameters were not so distinct around their true values. After inspecting many hydrographs, we could discover that the distinctions between the hydrographs are usually invisible to the naked eyes when their R^2 are larger than 0.99. This discovery indicates that it will be very difficult if we inflexibly want to get high precise parameters by manual calibration. Whether it is necessary to get so precise parameters is related to the model structure. If this is necessary, maybe we could not rely only on manual calibration although it is normally considered to be a realistic manner. Automatic calibration schemes can find the optimum much more efficiently than manual calibration on the basis of a fixed objective function. Its result will be more realistic than that of manual calibration if we ignore the overfitting caused by an unsuitable objective function. These two points indicate the necessity of automatic calibration schemes.

Another problem is the convergence criterion of the automatic calibration scheme when R^2 is adopted as the objective function. The magnitude of the alteration of R^2 with the parameters is small. There are limitations of the calculation accuracy in all kinds of computers. So, when R^2 is adopted as the objective function for calibrating insensitive parameters, it is possible that the optimal parameters can never converge into a desirable radius no matter which convergence criterion is selected. In other words, the objective function R^2 is not distinctive enough, i.e. the response surface of the objective function is too flat to force the optimum into the desirable radius. The magnitude of MSE is larger than that of R^2. So, we prefer MSE rather than R^2 in some cases, although they are uniquely related to each other. It is the same with any objective function if it is insensitive with the parameters. We should consider the alteration magnitude of an objective function carefully, and then select a suitable convergence criterion in designing an automatic calibration scheme.

Test 2: It is important to define suitable convergence indexes *Tol1* and *Tol2* in the POC. These two values are directly related to the convergence criterion of the scheme. If they are extremely small, a lot of computer time will be spent. If they are too large, the optimal values will not be reached. The convergence criterion, or convergence radius, relates not only to these two indexes, but also to the magnitude of the calibrated parameters and their sensitivity to the objective function. The parameters of the HBV model have different magnitudes. The different sensitivities of the parameters were studied by Harlin and Kung (1992) and also investigated in the test 1. So, the different *Tol1* and *Tol2* were defined for all calibrated parameters individually in the POC.

The different *Tol1* and *Tol2* were inspected in this test. In the ideal situation, only the parameter K_4 was auto-calibrated by the POC. We selected 0.03 as the initial value of K_4. The parameters, expect K_4, had their true values. The relations between *Tol1*, *Tol2* and K_4 are shown in Table 2-3.

Table 2-3. The relations between Tol1, Tol2 and K_4

Tol1	0.5	0.1	0.05	0.03	0.01	0.002	0.00002
Tol2	0.05	0.01	0.005	0.004	0.002	0.0002	0.00001
K_4	0.01987	0.02003	0.01994	0.01997	0.01996	0.01997	0.01997
R^2	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
True value: $K_4 = 0.02$							

In Table 2-3, the optimal values of K_4 tended to stability and were very close to its true value when *Tol1* was less than 0.03 and *Tol2* was less than 0.004. The same analysis was executed on parameter *UZL* (Table 2-4).

It is not easy to define suitable *Tol1* and *Tol2* when the POC is used in practical projects. The results derived in the ideal situation, such as Table 2-3 and Table 2-4, may be used as a reference. In order to guarantee against unrealistic solutions, the small values of *Tol1*=.00002 and *Tol2*=.00001 were adopted in the following tests of this part

of the report.

Table 2-4. The relations between Tol1, Tol2 and UZL

Tol1	0.6	0.2	0.1	0.01	0.05	0.001
Tol2	0.1	0.05	0.01	0.001	0.005	0.0001
UZL	20.763	20.580	20.015	19.991	20.000	20.001
R^2	.999615	.999732	.999996	1.000000	1.000000	1.000000
True Value: UZL = 20.0						

Test 3: The parameters K_4 and *Perc* were calibrated simultaneously. The order of the calibrated parameters was the same as that in the table. In the following tests as well, the order was the same as that in the corresponding tables, and Par means Parameters. The result of this test is shown in Table 2-5.

Table 2-5. The result of test 3

No.	1	2	3	1	2	3
Par.	Initial Values			Optimal Values		
K_4	0.030	0.005	0.050	0.0213	0.0220	0.0214
Perc	1.50	3.00	0.03	1.0066	1.0098	1.0070
R^2	.99864	.96489	.99421	1.00000	.99999	1.00000
True Values: K_4 =0.02, Perc=1.0						

The optimal values of the parameters were identical for three different sets of initial values and were close to the true values, although their initial values were far away from their true values. It looks as if the parameters K_4 and *Perc* will strongly interfere each other. Actually, they are independent, *Perc* controls the total amount of Q_4 (cf. Fig. 6 in Part I) and K_4 controls the shape of Q_4. But, it is unfortunate that not all the optimal values reach their true values exactly, especially K_4. This deviation may possibly be caused by the insensitive objective function described in test 1.

Test 4: The parameters K_4, *Perc* and *UZL* were calibrated simultaneously in this test. The result is shown in Table 2-6.

The result shows that true values were not reached even if the initial values were close to the true values, such as in No.5. The optimal values of No.2 to No.7 were located near the true values. There was a clear tendency that K_4 and *Perc* increase regularly with the decrease of *UZL*. It is possible to find different model parameter sets with the same R^2 and almost the same model performances. This shows that these three parameters will interfere with each other. The optimal values of No.1 located far away from the true values and were not in line with the alteration tendency.

Table 2-6. The result of test 4

No.	1	2	3	4	5	6	7
Par.	Initial Values						
K_4	0.010	0.050	0.024	.022	.022	0.015	0.030
Perc	2.00	0.20	1.40	0.09	0.90	1.20	0.05
UZL	25.0	26.0	24.0	22.0	22.0	18.0	15.0
R^2	.98367	.99665	.99542	.99674	.99954	.99935	.98450
Par.	Optimal Values						
K_4	0.0999	0.0080	0.0126	0.0137	0.0163	0.0254	0.0328
Perc	0.1107	0.6369	0.8283	0.8576	0.9276	1.0842	1.1678
UZL	24.003	21.543	20.665	20.548	20.275	19.686	19.364
R^2	.99689	.99936	.99984	.99989	.99996	.99995	.99980
True Values: $K_4 = 0.02$, *Perc = 1.0, UZL = 20.0*							

Test 5: In this test, there was one more parameter, K_1, as compared with test 4. The result is shown in Table 2-7.

Table 2-7. The result of test 5

No.	1	2	3	4	5	6
Par.	Initial Values					
K_4	0.005	0.150	0.022	0.100	0.018	0.350
Perc	0.10	1.50	0.09	0.30	1.10	2.00
UZL	17.0	23.0	22.0	26.0	18.0	15.0
K_1	0.50	0.30	0.25	0.40	0.18	0.10
R^2	.86581	.98792	.99280	.95692	.99928	.98196
Par.	Optimal Values					
K_4	0.1000	0.0396	0.0158	0.0124	0.0243	0.0309
Perc	2.2007	0.7823	0.7664	0.7590	1.1200	1.6111
UZL	29.126	21.901	21.085	21.032	19.459	16.809
K_1	0.2933	0.2042	0.2016	0.2014	0.1991	0.1936
R^2	.98552	.99916	.99977	.99973	.99994	.99864
True Values: $K_4 = 0.02$, *Perc = 1.0, UZL = 20.0,* $K_1 = 0.2$						

Neither of the optimal values reached the true values, even if the initial values were very

close to the true values, such as in No.5. The optimal values of No.1, as that in test 4, were far away from the true values. It is possible that there is a local optimum. The initial values of No.4 were further away from the true values than those of No.2, No.3 and No.6. But, the optimal values were closer to the true values than in the others.

Test 6 : The parameters *Maxbas* and K_0 were calibrated in this test. The result is shown in Table 2-8.

Table 2-8. The result of test 6. MB: Maxbas

No.	1	2	3	4	5
Par.	Initial Values				
MB	2	2	2	1	1
K_0	0.3	0.6	0.7	0.6	0.7
R^2	.87507	.94556	.95326	.96783	.93275
Par.	Optimal Values				
MB	1	1	2	1	2
K_0	0.4000	0.4000	0.7455	0.4000	0.7455
R^2	1.0000	1.0000	.95415	1.0000	.95416
True Values: MB = 1.0, K_0 = 0.4					

The optimal values of the parameters reached their true values if the initial values were not so far away from the true values. It was evident that No.3 and No.5 converged at a local optimum. The local optimum could be illustrated by the Fig. 2-1.

Maxbas	1	2
K_0		
0.30	.989	.875
0.35	.997	.893
0.40	1.00	.908
0.45	.997	.920
0.50	.991	.930
0.55	.981	.939
0.60	.967	.945
0.65	.951	.950
0.70	.932	.953
0.75	.912	.954
0.77	.903	.953

Fig. 2-1 The response of R^2 to K_0 and Maxbas

The model performance was very poor at the local optimum in Table 2-8 according to the visual hydrograph and R^2. The parameter *Maxbas* can easily be calibrated manually because its value is only an integer. The unsuitable *Maxbas* will clearly result in a visible poor model performance. We had better take *Maxbas* out of the automatic

calibration scheme in order to simplify the scheme and save the computer time, or not restrict it to integer values.

Test 7: The parameters *Fc* and *Lp* dominate the basin evaporation. They were calibrated in this test. The result is shown in Table 2-9.

Table 2-9. The result of test 7

No.	1	2	3	4	5
Par.	Initial Values				
Fc	280.0	150.0	250.0	290.0	100.0
Lp	0.95	0.90	0.75	0.65	0.65
R^2	.99512	.99224	.99660	.98750	.98539
Par.	Optimal Values				
Fc	216.794	211.668	193.931	182.457	182.427
Lp	0.8169	0.8122	0.7931	0.7785	0.7784
R^2	.99982	.99991	.99997	.99975	.99975
True Values: Fc = 200.0, Lp = 0.80					

Neither of the optimal values reached the true values. No local optimal points were found even though the initial values were far away from the true values, such as in No.5. The optimal values of Fc decreased with the decrease of *Lp*.

There was an interesting case in this test. The initial values of No.4 and No.5 were not the same. But, their optimal values were almost the same. So, the initial value of the first parameter is not important in the POC on condition that there are no local optima.

Test 8: There was one more parameter β in this test as compared with test 7. These three parameters dominate the runoff production. The result is shown in Table 2-10. The characters of the result were similar to that of the above results in many aspects.

Table 2-10. The result of test 8

No.	1	2	3	4	5
Par.	Initial Values				
Fc	100.0	170.0	180.0	230.0	290.0
Lp	0.95	0.85	0.83	0.75	0.65
β	3.5	2.5	2.2	1.8	1.0
R^2	.92939	.99652	.99895	.99826	.99074
Par.	Optimal Values				
Fc	298.114	233.101	214.967	182.972	139.654
Lp	0.9221	0.8555	0.8282	0.7603	0.6030
β	3.231	2.417	2.192	1.178	1.215
R^2	.99680	.99963	.99992	.99986	.99802
True Values: Fc = 200.0, Lp = 0.8, β = 2.0					

Test 9: In this test, the calibrated parameters and their initial values were the same as that of test 8. But, the orders were not the same. The different results for two different orders are shown in Table 2-11 and Table 2-12.

Table 2-11. The result of test 9 with order 1

No.	1	2	3	4	5
Par.	Initial Values				
β	3.5	2.5	2.2	1.8	1.0
Fc	100.0	170.0	180.0	230.0	290.0
Lp	0.95	0.85	0.83	0.75	0.65
R^2	.92939	.99652	.99895	.99826	.99074
Par.	Optimal Values				
β	2.200	2.158	2.093	1.778	2.928
Fc	206.872	209.930	205.930	183.698	276.469
Lp	0.8202	0.8209	0.8127	0.7619	0.9029
R^2	.99994	.99995	.99998	.99987	.99808
True Values: β = 2.0, Fc = 200.0, Lp = 0.8					

Table 2-12. The result of test 9 with order 2

No.	1	2	3	4	5
Par.	Initial Values				
Lp	0.95	0.85	0.83	0.75	0.65
β	3.5	2.5	2.2	1.8	1.0
Fc	100.0	170.0	180.0	230.0	290.0
R^2	.92939	.99652	.99895	.99826	.99074
Par.	Optimal Values				
Lp	0.6000	0.7718	0.7800	0.8203	0.8804
β	1.211	1.852	1.894	2.131	2.691
Fc	140.408	188.220	191.544	210.409	251.679
R^2	.99228	.99993	.99996	.99996	.99909
True Values: Lp = 0.8, β = 2.0, Fc = 200.0					

The results with three different orders were significantly different. The optimal values of the three parameters in Table 2-11 were all much closer to their true values than those in Table 2-10, and the corresponding R^2 were also greater than that in Table 2-10.

Comparing the results in Table 2-11 and Table 2-12, the results of No.4 and No.5 in Table 2-12 were better then that in Table 2-11. As far as No.2 and No.3, it is difficult to say which one was better than another, and R^2 were nearly the same. But, the optimal values were not the same.

The optimal values with different initial values were all very different in the three tables. The optimal values of No.1 in Table 2-12 were very far away from the true values. The parameter *Lp* reached the minimal value in its respective range suggested by the POC. But, it was also a good model performance and the R^2 was larger than 0.99. We cannot see its deviation in hydrograph by the naked eyes.

These three parameters are interdependent according to the model structure. But, their sensitivities are not the same, i.e. the mutual interferences caused by the deviations of the parameter values are not the same. We had better analyse the sensitivities of all the model parameters and order the sensitive parameters in the front of the parameter set because the interference of the insensitive parameter to sensitive parameter is relatively small.

Test 10: Totally nine parameters were calibrated simultaneously in this test. The relations between the parameters are very complicated. So, only small alterations of the initial values were considered in this test. The parameter order was that suggested by the POC. The result is shown in Table 2-13.

Table 2-13. The result of test 10. MB: Maxbas.

Par.	Initial	Optimal	Initial	Optimal	Initial	Optimal	Average
MB	1	1	1	1	1	1	1
Fc	230.0	207.328	180.0	201.318	170.0	209.154	205.933
Lp	0.75	0.8059	0.83	0.7735	0.75	0.8005	0.7933
β	2.30	2.0883	1.80	2.0247	2.40	2.0733	2.0621
K_1	0.17	0.2143	0.22	0.1896	0.24	0.1908	0.1983
K_0	0.35	0.3945	0.43	0.4034	0.42	0.4106	0.4028
UZL	24.0	19.643	18.0	19.858	22.0	19.567	19.689
Perc	1.30	1.0149	0.80	0.9436	1.20	1.0238	0.9941
K_4	0.016	0.0209	0.022	0.0194	0.024	0.0211	0.0205
R^2	.97742	.99981	.99020	.99967	.99446	.99987	.99995
True Values: MB = 1, Fc = 200.0, Lp = 0.8, β = 2.0, K_1 = 0.2, K_0 = 0.4, UZL = 20.0, Perc = 1.0, K_4 = 0.02							

The result was satisfactory. The optimal values of parameters were reached as long as the initial values were not so far away from the true values. But, the optimal values of all parameters did not reach their true values. The values in the last column in the table are the average of the corresponding three optimal values, except R^2. The R^2 with this set of parameters is 0.9999470 and is larger than the others. It is an interesting discovery.

3. TEST IN THE REAL SITUATION

The real situation means that the actual observed discharge was adopted as the output of the basin. This is the normal situation. The characters of the POC were inspected in the actual basin, Hushile with the real observed discharge. All parameters were calibrated simultaneously, except the snow routine. The *Tol1*, *Tol2* and the parameter order suggested in the POC were adopted. The result is shown in Table 2-14.

The initial values of the first set of parameters were the manual calibration results derived by the author and those of the second set were arbitrary values. Some of their optimal values were significantly different, such as β and *Perc*. The third set of initial values were selected between two former optimal sets and was better than the two former optimal sets according to R^2. The optimal values of the third set were the best values among all of these results according to R^2. The parameters in the last column were the averages of three former optimal values and the corresponding R^2 was not the best one. We have an impression that the optimal values are closely related with the initial values.

Table 2-14. The result in the real situation. MB: Maxbas, Par: Parameters

Par.	Initial	Optimal	Initial	Optimal	Initial	Optimal	Average
MB	1	1	1	1	1	1	1
Fc	250.0	185.893	160.0	196.358	190.0	195.8240	192.692
Lp	0.75	0.6059	0.70	0.5526	0.57	0.5502	0.5696
β	4.0	4.9098	5.0	6.3162	5.5	5.9960	5.7407
K_1	0.30	0.3692	0.50	0.4975	0.43	0.4300	0.4322
K_0	0.45	0.4767	0.30	0.3532	0.41	0.4275	0.4192
UZL	18.0	18.900	22.0	20.539	19.5	19.500	19.646
$Perc$	0.3	0.9423	1.3	2.1534	1.5	1.7955	1.6304
K_4	0.023	0.0997	0.070	0.0996	0.099	0.0996	0.0997
R^2	.85216	.86032	.852890	.86146	.86150	.86220	.86186

4. DISCUSSION AND CONCLUSIONS

Some parameters of the HBV model are not sensitive enough to the objective function R^2. This will make it difficult to construct a suitable objective function of the automatic calibration scheme for the model parameters.

The automatic calibration scheme POC is an efficient scheme for the fine-tuning of the HBV model parameters. We may get a set of optimal parameters as long as the initial values of the parameters do not deviate from the optimal values too far. There are two main problems discovered in the research. One is the different optimal values of the parameters with the different initial values and the different orders. Sometimes the deviations are considerably large. Another one is that the optimal values of the parameters cannot reach their true values in the ideal situation. There are probably two reasons for these two problems. One is the insensitivity and the mutual interference of the model parameters, which make it difficult to construct effective objective functions. Another one is the iteration loop strategy. Because some parameters interact, they should perhaps be optimized simultaneously.

There are not so many local optima of the model parameters according to the test results. But, the response surfaces of the objective functions are flat. The parameter Maxbas should be taken out of the automatic scheme.

PART III

DEVELOPMENT OF A NEW AUTOMATIC CALIBRATION SCHEME FOR THE HBV MODEL

ABSTRACT

A new automatic calibration scheme for the HBV model (ACSH) was developed in this part. The ACSH was based on the physical significance of the model parameters, the model structure, the experience of the manual calibration in practice, and the results of the tests pursued in this part. The inference of the specialists in manual calibration was adopted as the guideline of the ACSH. A fine modification of the model structure of the soil routine was suggested. Totally nine parameters, excepting the snow routine, were calibrated automatically in two stages, firstly the soil moisture routine and then the others. The first stage is independent of the second stage because of the special objective function. So, the result of the first stage is more realistic than some existing schemes. All the calibrated parameters were composed into six different parameter sets, i.e. the six steps. The parameters acting on the same element were integrated into one set, and were then calibrated simultaneously by use of the Powell method (Press et al., 1992). The sets were in a fixed order in the ACSH according to their relationships. The different objective functions have been selected very carefully for the different sets. There were stable optimal values of the model parameters with different initial values varying in a considerable range when the ACSH was tested in the Hushile basin and the Salvajina basin. This character is a merit of the ACSH. The solutions of the ACSH are realistic and reasonable, and give the same model performances as the manual calibration. It could thus be used as a reference or an alternative solution of the model.

1. INTRODUCTION

The HBV model has been applied widely and is a successful conceptual hydrological model (Bergström, 1992). It is used not only for flood forecasting but also for some other purposes, such as the inflow forecasting for hydro-power reservoirs, spillway design of reservoirs, water resources evaluation, water quality estimation, and so on.

As mentioned in Part II, the calibration of the model parameters is an important but difficult problem in a model application. Usually, it is completed by skilled hydrological experts. The manual calibration is considered as the most realistic way. But, it not only is a tedious procedure but also requires profound knowledge about the model structure and parameters. Besides, there will be different results for different operators, and calibration qualities are often related closely to the skill and the knowledge of the operators. So, it is desirable to develop automatic calibration schemes for hydrological models.

Many model designers have developed schemes for their models, including the POC for the HBV model (Harlin, 1991). Most of them claimed that their schemes perform well in practice. These schemes teem with the valuable knowledge, utilizable technique and also the failed experience, which may be used as references in developing a new scheme for the HBV model.

The HBV model has been applied in many basins for several decades. We understand the model structure and the actions of the model parameters well. A lot of experience for manual calibration has been accumulated in applications. So, there has been a solid foundation to establish an automatic calibration scheme.

Most of the parameters of the HBV model have a physical significance and definition. But, it is very difficult to determine their values according to their physical definitions because of the lack of observed data in practice. These parameters, coupled with the free parameters, should be calibrated on the basis of the observed discharge. This problem is one of the difficulties in parameter calibration, especially in automatic calibration schemes. Another difficulty is the interferences between the parameters. It is a common weakness of the model structure in all hydrological models. It is very difficult to completely eliminate the interferences in a model. This weakness will cause an indefinite solution, i.e., there will be different parameter sets with almost the same model performance. Sometimes, the optimal parameters will go far against their physical definitions in automatic calibration schemes.

Because the advanced computers make it very easy to attempt every assumptions, some designers paid much more attentions to automatic optimization method than to hydrological models' themselves. It has been demonstrated that the automatic calibration scheme for a hydrological model could not rely only on the careful design in automatic optimization method. A hydrological model is a very complicated system. There are complicated correlations between the parameters and the different elements of the model structure. Thereby, as mentioned above, there are some difficulties in parameter calibration. These problems should be solved relying mainly on the physical significance and the actions of the parameters as well as the model structure, instead of on the careful design of automatic optimization methods only.

In this part, a new automatic calibration scheme for the HBV model (ACSH) was developed. Firstly, some useful objective functions are listed and described. Secondly, some meaningful tests are given. Then, the ACSH is addressed. Finally, the tests of the ACSH in the Hushile basin and the Salvajina basin is presented.

2. OBJECTIVE FUNCTIONS

The objective function is one of the most important elements in an automatic optimization scheme. The suitable objective functions are the key of a successful scheme. Different objective functions lay particular stress on the different model agreement. We should select the different objective functions carefully for the different parameters on the basis of their actions. Several objective functions are listed and described below. Some of them were adopted in the ACSH and some of them were used

for tests only.

$$func1 = 1 - \frac{\sum_{j=1}^{n} (Q_c(j) - Q_o(j))^2}{\sum_{j=1}^{n} (Q_o(j) - Q_{om})^2} \qquad (3\text{-}1)$$

where n = number of timesteps in whole calibration period,
$Q_c(j)$ = calculated discharge,
$Q_o(j)$ = observed discharge,
and

$$Q_{om} = \frac{1}{n} \sum_{j=1}^{n} Q_o(j) \quad .$$

The *func1* is the efficient criterion R^2 (Nash and Stutcliffe, 1970). The R^2 could be used to inspect the model agreement synthetically. We may get an integrative view about the model performance in it.

$$func2 = \sum_{j=1}^{n} (Q_c(j) - Q_o(j))^2 \qquad (3\text{-}2)$$

The *func2* is the sum of square errors. It has the same physical meaning as the R^2. But the magnitude of its alteration with the parameters is larger than the R^2. It is its advantage in automatic optimization schemes in some cases.

$$func3 = \left| \sum_{j=1}^{n} (Q_s(j) - Q_o(j)) \right| \qquad (3\text{-}3)$$

$Q_s(j)$ is the calculated runoff, which depends only on the parameters of soil moisture routine. The *func3* is the absolute accumulated volume error.

$$func4 = \sum_{l=1}^{m} \left| \sum_{j=1}^{n_m} (Q_s(j) - Q_o(j)) \right| \qquad (3\text{-}4)$$

The *func4* is the sum of the *sub-func3*, which means that the whole calibration period is split into several sub-periods and the *func4* equals the sum of the *func3* in every sub-period. Where m is the number of the sub-periods, n_m is the number of timesteps in sub-period m and

$$n = \sum_{l=1}^{m} n_m \quad .$$

The principle of splitting into sub-periods is that the runoff is corresponding to the rainfall clearly in a sub-period. Comparing the *func3*, the *func4* could be used to inspect the runoff agreements in all the sub-periods.

The runoff volume in a period is very important and useful information derived from the observed discharge. In the *func4*, it could be made full use of. If there are no lakes, the

func4 depends only on the parameters of the soil moisture routine because only calculated runoff is adopted in it, which is a merit.

$$func5 = func4 + obw * func3 \qquad (3-5)$$

The *func5* is a mixture of the *func3* and the *func4*, where *obw* is a weight.

$$func6 = \sum_{j=1}^{n} | (Q_c(j) - Q_o(j)) * Q_o(j) | \qquad (3-6)$$

The aim of the *func6* is to enhance the flood peak agreement.

$$func7 = \sum_{j=1}^{n} | LogQ_c(j) - LogQ_o(j) | \qquad (3-7)$$

The aim of the *func7* is to enhance the base flow agreement.

3. TEST RUNS

Several dozen of tests, including different parameter sets and different objective functions, were made in the Hushile basin (cf. Part I). The different subjective initial values were inspected in every test. These tests could be used to reveal the characters, the actions and the mutual interferences of the parameters. In this section, only the tests with the meaningful results are listed. In most of the tests, only a part of the parameters were calibrated. The remaining uncalibrated parameters were given the values in Table 2-14 of Part II.

Test 1: All model parameters were calibrated simultaneously in two situations, the ideal situation (cf. Part II) and the real situation. The objective function was the *func2*. The results are shown in Table 3-1

Table 3-1 The results of test 1

No.	Ideal				Real			
	1	2	1	2	1	2	1	2
Par.	Initial values		Optimum values		Initial values		Optimum values	
Fc	230.0	170.0	200.1	200.1	210.0	190.0	348.1	299.1
β	2.50	2.50	1.99	1.99	5.50	6.00	12.70	9.37
Lp	.75	.95	.800	.799	.60	.55	.285	.122
K_0	.430	.440	.4002	.4001	.450	.400	.3242	.3844
K_1	.160	.150	.1999	.1999	.400	.450	.5010	.4644
UZL	16.0	26.0	19.99	20.00	18.0	21.0	15.31	15.02
Perc	1.50	.70	1.000	1.000	1.60	1.85	4.628	4.649
K_4	.025	.015	.0199	.0199	.08	.10	.2406	.2576
R^2	.9949	.9926	1.000	1.000	.8618	.8623	.8645	.8640

The optimal values reached their true values regardless of initial values in the ideal situation. But, in the real situation, the optimal values were not stable with the different initial values, especially Fc, β and Lp.

In the ideal situation, there is was a unique solution. The real situation is much more complicated than the ideal situation. We can not guarantee that a scheme, which is successful in the ideal situation, will be successful also in the real situation. So, all the following tests were also executed in the real situation.

Test 2: The parameters *Fc*, β and *Lp* were calibrated simultaneously with two different objective functions. The results are shown in Table 3-2.

Table 3-2 The results of test 2

No.	1	2	3	4	5
Par.	Initial Values				
Fc	200.0	180.0	220.0	800.0	100.0
β	5.50	6.50	4.50	30.0	3.00
Lp	0.60	0.65	0.70	0.40	0.70
R^2	.8621	.8604	.8589	.8636	.8528
Par.	Optimal Values with the func2				
Fc	736.0	418.0	804.9	802.1	771.7
β	23.55	13.10	25.82	25.76	24.74
Lp	0.362	0.100	0.391	0.400	0.885
func2	366194.	367848.	366199.	366199.	366209.
R^2	.8642	.8636	.8642	.8642	.8642
Par.	Optimal Values with the func4				
Fc	366.7	1163.1	194.5	1096.9	165.8
β	7.22	21.36	4.13	19.46	3.60
Lp	0.857	0.994	0.743	0.164	0.700
func4	2685.46	2353.05	2740.79	2421.91	2746.17
R^2	.8580	.8569	.8584	.8549	.8584

These three parameters interfere with each other. The optimum values with different initial values were far away from each other, especially *Fc*. But, the model performances with the different optimal value sets were nearly the same according to R^2 and the hydrographs. Some other objective functions were also tried with similar results. This indicates that it will be very difficult to calibrate these three parameters simultaneously in a scheme.

But, the ratios of β to *Fc* were much more stable than their optimal values, especially when using the same objective functions, which means that it will be very easy to

calibrate one of them when the other one has been fixed.

Test 3: Only two parameters *Fc* and β were calibrated simultaneously with different objective functions and different *Lp*. The focuses of this test are the relationship of β to *Fc* and the effects of the different objective functions. The results are shown in Table 3-3.

Table 3-3 The result of test 3

No.	1	2	3	1	2	3
Par.	Initial Values					
	Lp=0.75			Lp=0.80		
Fc	300.0	300.0	100.0	300.0	300.0	100.0
β	7.0	4.0	4.0	7.0	4.0	4.0
R^2	.8587	.8487	.8600	.8613	.8484	.8540
Par.	Optimal Values with the func2					
Fc	737.1	739.6	740.6	739.1	734.6	739.9
β	23.70	23.74	24.51	23.73	23.62	23.75
func2	366193.	366193.	366254.	366193.	366194.	366193.
R^2	.8642	.8642	.8642	.8642	.8642	.8642
Par.	Optimal Values with the func3					
Fc	219.95	448.05	279.0	258.4	636.5	638.4
β	6.00	4.36	5.00	7.00	5.20	5.02
func3	0.	0.	0.	0.	0.	0.
R^2	.8611	.8371	.8564	.8612	.8288	.8287
Par.	Optimal Values with the func4					
Fc	233.4	220.3	228.9	284.2	279.4	283.7
β	4.47	4.37	4.43	5.48	5.43	5.47
func4	2737.53	2737.20	2737.20	2721.15	2721.61	2721.19
R^2	.8574	.8579	.8576	.8576	.8577	.8576

The optimal values with the different *Lp* were different. Some other *Lp* were tried too. The differences of the optimal values would be enlarged with *Lp*, including that with the *func2*. It is because *Fc* and *Lp* control the evaporation calculation together.

The results with the *func2* were stable. But, the optimal values were clearly unreasonable in physical significance, and depended on the parameters of other routines.

The *func3* is the absolute accumulated runoff volume error. The values of the *func3* were always equal to zero in the results. But, the optimal values of the parameters

scattered in wide ranges. Actually, in most cases, we may adjust only one parameter to make the *func3* reach zero.

The optimal values of the parameters with the *func4* were much more stable than with the *func3* and much more reasonable than with the *func2*.

The accumulated volume error of the whole period can not be guaranteed to become zero when the *func2* or the *func3* were adopted. Sometimes the errors will be considerably large.

The optimal values were very different with the different objective functions. Some of them were clearly unreasonable. But, like in test 2, the ratios of β to *Fc* were much more stable than their optimal values.

Test 4: In this test, the model structure of the soil moisture routine was modified slightly. A parameter *Ce* was introduced into the routine. It is used to correct the deviation between the observed potential evaporation rate of the pan and the real potential evaporation rate of the basin, i.e. the latter is equal to the former multiplied by *Ce*. The latter is used in the model instead of the former. The parameters *Ce*, β and *Lp* were calibrated simultaneously with the *func4*. There were many results with the different initial values. A part of these results are shown in Table 3-4.

The optimal values were close to each other. Only a few of them went a little far. Their average values were very stable. Furthermore, the average values were more and more stable with the increase of the samples. But, the absolute accumulated volume errors in the whole period, i.e. the *func3*, were large.

Table 3-4 A part of the results of test 4

No.	1	2	3	4	5	6
Par.	Initial Values					
Ce	1.050	1.020	1.100	0.950	.990	.940
β	5.70	5.00	3.00	7.00	3.50	3.00
Lp	0.57	0.70	0.60	0.70	0.50	0.55
R^2	.8627	.8609	.8476	.8568	.8576	.8548
Par.	Optimal Values with the func4					
Ce	.986	.986	.983	.986	.988	.989
β	3.737	3.890	3.572	3.888	3.952	3.823
Lp	0.682	0.700	0.655	0.700	.711	0.696
func4	2734.8	2731.4	2743.3	2731.4	2731.9	2734.4
func3	86.24	93.71	91.48	93.70	90.35	82.95
R^2	.8578	.8582	.8574	.8582	.8583	.8580

Test 5: This test was the same as test 4 but the parameter β was extracted. There were many results too and only a part of them, corresponding to test 4 in initial values, are shown in Table 3-5.

Table 3-5 A part of the results of test 5

No.	1	2	3	4	5	6
Par.	Initial Values					
Ce	1.050	1.020	1.100	0.950	.990	.940
Lp	0.57	0.70	0.60	0.70	0.50	0.55
R^2	.8628	.8615	.8611	.8586	.8619	.8588
Par.	Optimal Values with the func4					
Ce	0.997	0.997	0.997	0.997	1.000	0.997
Lp	0.822	0.823	0.822	0.824	0.835	0.824
func4	2773.7	2773.3	2733.7	2773.3	2772.7	2773.2
func3	99.90	100.57	99.96	100.79	106.99	101.17
R^2	.8583	.8583	.8583	.8583	.8580	.8582

Compared with test 4, the optimal values with the different initial values in this test were very stable. But, the *func3* were still large.

Test 6: The parameters *Ce* and *Lp* were calibrated with the *func5* in this test. Two sets of initial values were tried. The aim of this test is to inspect the *obw* of the *func5*. The results with the different *obw* are shown in Table 3-6.

Table 3-6 The results of test 6

No.		1	2	3	4	5
Obw		0.04	0.05	0.06	0.07	0.08
Par.	Initial	Optimal values with the func5				
Ce	.95	1.008	1.005	1.012	1.024	1.028
Lp	0.80	0.755	0.748	0.758	0.779	0.790
func5		374.52	374.83	375.12	375.22	376.24
func3		31.973	38.822	20.977	0.000	-0.016
Ce	1.03	1.005	1.005	1.017	1.015	1.015
Lp	0.77	0.754	0.755	0.756	0.751	0.752
func5		374.46	374.83	475.08	375.12	375.14
func3		36.905	37.004	0.128	0.025	0.025

The *func5* consists of two parts (Equ. 3-4), the runoff agreements in all sub-periods and in the whole period. The *obw* was used to adjust the weights in the objective function. It is evident in Table 3-6 that the *func3* were small but the optimal values were different with the different initial values when *obw* were large, and the optimal values were the same but the *func3* were large when *obw* were small.

It is possible to find a suitable *obw* and then get not only stable solutions with different initial values but also considerably small values of the *func3*, such as No.3 in Table 3-6. The suitable value of *obw* depends on the sub-periods splitting, the different basins and also the wish of the user. The principle is that the value of the *func3* could be forced into an acceptable range and the optimal values of the parameters are stable relatively with different initial values.

Test 7: The parameters K_0, K_1, *UZL*, *Perc*, K_4 and *Lag* were calibrated simultaneously with the *func2*. The parameter *Lag* is used to simulate the damping of flow in the river network within a sub-basin. The results of this test are shown in Table 3-7.

Table 3-7 The results of test 7

No.	1	2	3	4	5	6
Par.	Initial Values					
K_0	0.430	0.500	0.400	0.600	0.450	0.410
K_1	0.330	0.350	0.410	0.380	0.300	0.400
UZL	14.0	15.0	26.0	25.0	13.0	17.0
Lag	0.70	0.72	0.69	0.65	0.68	0.71
Perc	2.10	1.30	1.80	0.80	0.60	1.90
K_4	0.006	0.070	0.008	0.050	0.130	0.020
R^2	.8529	.8572	.8553	.8636	.8604	.8573
Par.	Optimal Values with the func2					
K_0	0.518	0.527	0.496	0.508	0.523	0.507
K_1	0.356	0.350	0.384	0.371	0.352	0.364
UZL	24.39	24.37	23.86	24.35	24.35	23.21
Lag	0.627	0.627	0.626	0.625	0.627	0.628
Perc	0.492	0.484	1.237	0.923	0.488	0.949
K_4	0.0036	0.0035	0.0800	0.0523	0.0038	0.0541
Func2	358311.	358312.	359443.	359283.	358310.	359298.
R^2	.8671	.8671	.8667	.8668	.8671	0.8668

The optimal values were close to each other except Perc and K4. The parameter K4 was increased with *Perc*.

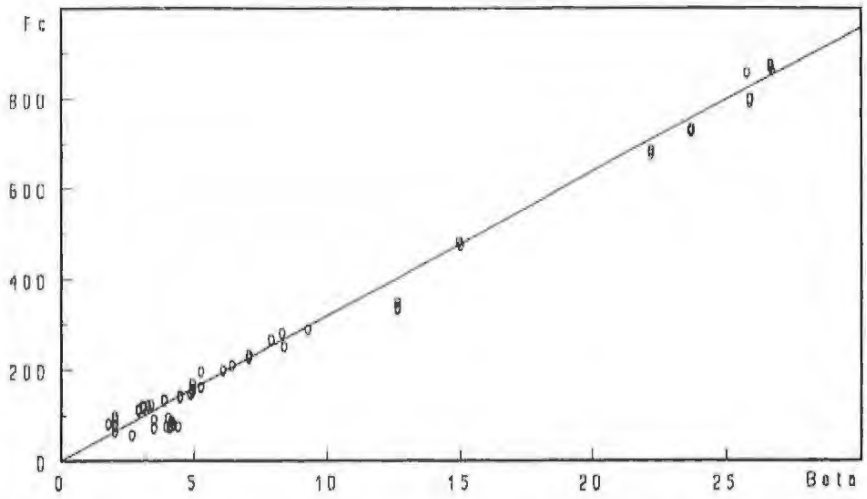

Fig. 3-1 The relationship of the optimal values of Fc and Beta of the tests

4. AUTOMATIC CALIBRATION SCHEME FOR THE HBV MODEL

The parameters of the HBV model have different actions in the model. Most of them have a clear physical significance. In manual calibration, the parameters are adjusted by a specialist according to their special actions in the model and their physical significance. Firstly, the agreement of runoff volume is inspected and the parameters of the soil moisture routine are calibrated. Thereafter the other parameters are adjusted according to the agreement of the hydrograph. The parameters K_0, *UZL* and *Lag* are modified to agree with flood peak agreement, *Perc* and K_4 for base flow agreement, and so on. In practice, manual calibration has been proven to be good for calibration of the parameters. So, it has been adopted as the guideline of the ACSH to simulate the inference of the specialists in manual calibration.

In this section, the ACSH is described. The scheme was based on the physical significance of the model parameters, the model structure, the experience of the model applications, and the results of the tests mentioned above. Totally nine parameters, excepting the snow routine and *MAXBAS*, were automatically calibrated in two stages, firstly the soil moisture routine and then the others. In the first stage, a parameter *Ce* was introduced into the soil moisture routine and the parameters were calibrated in two steps. In the second stage, the remaining parameters were calibrated in four steps with the different objective functions.

The automatic optimization method adopted in the ACSH is the Powell (Press et al., 1992).

4.1. First stage

The soil moisture routine is used to calculate the runoff. The parameter calibration of this routine is the most difficult part. Many tests with this routine were made with the different parameter sets and different objective functions. In these tests, such as test 2,

it was found that the parameters *Fc*, β and *Lp* interfere each other strongly. The optimal values scattered in very large ranges. Furthermore, some of them were extremely large or small and were clearly unreasonable to their physical definitions. This interference is governed by the model structure of this routine. So, it will be very difficult to calibrate these three parameters simultaneously in an automatic calibration scheme.

It was also found in these tests, such as test 2 and test 3, that the ratios of the optimal values of β to *Fc* were much more stable than their values' themselves, especially that with the same objective function. The results of some tests are shown in Fig. 1. There are about sixty points in the figure.

It is quite evident in Fig. 1 that all the points are located around a straight line regardless whether their values are reasonable or not, which means that there is a close relationship between these two parameters. It is in line with the experience from manual calibration. Therefore, *Fc* was fixed before the automatic calibration. If it is possible, we could get the stable solution of β and also eliminate the interaction between *Fc* and *Lp* in evaporation calculation.

The parameter *Fc* has a clear physical definition. It expresses the tension soil moisture capacity of a basin. A lot of knowledge about its value has been accumulated in the model applications. It should, in theory, be possible to estimate its value according to the climatic, geological, geographic and hydrologic conditions of a basin before the parameter calibration.

The parameter *Fc* acts on the evaporation calculation. In order to fix *Fc* before the calibration, a parameter *Ce* was introduced into this routine in the ACSH. The calculated evaporation is adjusted by *Ce* and *Lp*. In this case, the calibrated parameters are *Ce*, β and *Lp* in the soil moisture routine. In test 4 and test 5, it has been verified that these three parameters could be calibrated simultaneously in a scheme.

So, the first step of this stage was to calibrate *Ce*, β and *Lp* simultaneously on condition of the fixed *Fc*. The objective function was the *func5*. Around the initial value set selected by the user, ten other random initial value sets were tried automatically at the same time. And then there will be eleven optimal value sets totally. Owing to the interference of these parameters, these optimal values could not converge absolutely. But, they would be all located into considerable small ranges, and the arithmetic average of the optimal values of β would be considerable stable. According to the tests, the eleven random sets are enough to get the considerably stable β. Hence, only β was fixed at the average value at this step.

The second step was to calibrate *Ce* and *Lp* simultaneously on condition of the fixed *Fc* and β. Again, the objective function was the *func5*. Like in the first step, eight other initial value sets were also tried automatically. The parameters *Ce* and *Lp* were fixed at one optimal value set with the minimum objective function value among the nine sets.

The calibration of this stage is independent of all other parameters if there are no lakes in a basin because of adopting the *func5*. And then the result will be much realistic.

The parameter *Lp* used in the ACSH was the absolute value of soil moisture, in which the soil moisture evaporates in potential evaporation rate.

4.2. Second stage

The parameters K_0, K_1, *UZL*, *Perc*, K_4 and *Lag* were calibrated in this stage. This stage is much simpler than the first stage. The first step was to calibrate these six parameters simultaneously with the *func2*. Like in the first stage, several other initial value sets were inspected automatically. According to the test 7, the optimal values of this step would be considerably stable. Hence, one optimal value set with the minimum objective function value was adopted as the result of this step. The stability of this step is the solid foundation of this stage.

The *func2* may only be used to inspect the hydrograph agreement synthetically and is not the only standard to judge the model performance. Actually, in manual calibration, specialists inspect the agreements of the different parts of the hydrograph, and then adjust the corresponding parameters. So, the following three steps were designed in the ACSH.

The second step was to calibrate the parameters K_0, *UZL*, and *Lag* simultaneously with the *func6*. The other three parameters used the results in the first step. The aim of this step is to enhance the flood peak agreement.

The third step was to calibrate the parameters *Perc* and K_4 simultaneously with the *func7*. The parameters K_0, *UZL* and *Lag* used their optimal values in the second step, and K_1 used its optimal value in the first step. The aim of this step is to enhance the base flow agreement.

The fourth step was to calibrate K_1 only with the *func2*. The remaining parameters used their optimal values correspondingly in the second step and the third step. After the second and third steps, it is necessary to readjust K_1.

In the second, third and fourth steps, like the above steps, several initial value sets were tried automatically too and the parameters were fixed at one optimal value set with the minimum objective function value among all the optimal sets. Trying several initial value sets automatically is very useful to avoid the local optima.

After the last three steps, a little quality of R^2 will be lost. But, the result will be more realistic because these steps were designed on the basis of the actions of the parameters. It is very easy to shift the objective functions in order to enhance the different agreements if it is necessary.

In summary, there were six steps in the ACSH.

Step 1: The parameters *Ce*, β and *Lp* were calibrated with the *func5*, but only β was fixed.

Step 2: The Parameters *Ce*, and *Lp* were calibrated and fixed with the *func5*.

Step 3: The parameters K_0, K_1, *UZL*, *Perc*, K_4 and *Lag* were calibrated with the *func2* to get better initial estimates for the following steps.

Step 4: The parameters K_0, *UZL* and *Lag* were calibrated and fixed with the *func6*.
Step 5: The parameters K_4 and *Perc* were calibrated and fixed with the *func7*.
Step 6: The parameter K_1 was calibrated and fixed with the *func2*.

In the ACSH, only a part of the parameters of the HBV model were considered. So, it could only be tried out in the basin without snowpack or after snow routine at present status.

5. TESTS OF THE ACSH IN TWO BASINS

The ACSH was tested in two basins, the Hushile basin and the Salvajina basin in this report.

The Hushile basin is a Chinese basin (cf. Part I). In this basin, the ACSH was tested in the different *Fc*, *obw*, and arbitrary initial values. The results are listed in Table 3-8(1) (*Fc*=200) and Table 3-8(2) (*Fc*=180). In order to inspect the effect of *Fc*, the results with the different *Fc* are listed. The first blocks in the tables are the different arbitrary initial values. The second and third blocks are the optimal values with the different *obw*.

The Rio Cauca is one of the main Colombian rivers. It flows from south to north between the mountain ranges Cordillera Occidental and Cordillera Central in western Colombia. The Salvajina basin is located in the upper reach of the river and covers an area of 3652 km^2. This region is located within the zone that is influenced by the intertropical convergence. So, there is rich precipitation. The floods are caused by long periods of rain and not by occasional rainstorms. This hydrological regime is clearly different from that in the Hushile basin. The computed inflow to the Salvajina reservoir is available. Totally, the observed data of eight years (1975-1982) were adopted as the calibration period. Similarly, the results of the ACSH in this basin are listed in Table 3-9(1) (*Fc*=300) and Table 3-9(2) (*Fc*=260).

In the Hushile basin, we refer the result of No.5 of the second block in Table 3-8(1) to result 1 and in Table 3-8(2) to result 2. The hydrographs corresponding to the result 1, the result 2 and the result from the POC (cf. Part I) are plotted in Fig. 3-2. Similarly, in the Salvajina basin, they are referred to as result 3 and result 4. The hydrographs corresponding to the result 3, the result 4 and the result of manual calibration (Häggström et al., 1988) are plotted in Fig. 3-3.

In the Salvajina basin, the result 3 and the result 4 were verified in an extrapolation period (1983-1984). The R^2 are 0.9013 and 0.9085 in this period. The hydrographs are plotted in Fig. 3-4.

It is quite clear that the optimal values of the parameters with the different initial values were considerably stable. Every set, except that with the relatively large *func3*, could be adopted as the solution. It is evident that model performs well in both the calibration period and extrapolation period and the differences between these computed hydrographs are invisible.

There was no distinct difference between the results with the different *obw*. The *func3* usually decreased with the increases of *obw*. According to the values of the *func3* in the tables, any values located in the ranges of 0.080 to 0.084 in the Hushile basin and 0.045 to 0.050 in the Salvajina basin are suitable to be adopted as *obw*. So, it is not difficult to select the suitable *obw*.

There were some differences between the optimal values of the parameters with the different *Fc* because there are some interactions between *Fc* and other three parameters in soil moisture routine. But, the differences were not so large. Particularly, these results could give almost the same model performance according to the R^2 and hydrographs in Fig. 3-2 and Fig. 3-3. The small deviation of *Fc* will not destroy the reasonableness of the solution.

In the Salvajina basin, the parameter β will converge at about 0.6 if there is no restriction. This value is not reasonable although the model performs even better in this value than in the present solution. So, it was restricted to be not less than 1 on the basis of its physical definition (see Bergström, 1976). In this case, β always reached its lower boundary in the ACSH. And then only *Ce* and *Lp* were actually calibrated. So, the optimal values of them were very stable. If we want to get reasonable result of β without the restriction, maybe we should refine both the scheme and the model structure.

In the Salvajina basin, it was very clear that all results of the second stage converged to two points, especially the parameters K_0 and *UZL*, such as the result 3 and result 4. This is because K_0 and *UZL* will interfere with each other. But, there is no evident difference between these two kinds of solutions according to R^2 and Fig. 3-3.

Comparing the R^2 of the third step and the sixth step, it was reduced only in about 0.006 in the Hushile basin and 0.0004 in the Salvajina basin.

Table 3-8(1) The results of the ACSH in the Hushile basin (Fc=200)

No.	1	2	3	4	5
Par.	Initial Values				
Ce	1.00	1.15	1.05	0.95	1.10
β	6.0	3.0	4.0	5.0	2.0
Lp	30.0	25.0	20.0	35.0	45.0
K_0	.42	.30	.35	.45	.60
K_1	.43	.25	.35	.45	.30
UZL	20.	30.	15.	23.	25.
Lag	.70	.60	.80	.60	.40
Perc	1.00	2.00	1.50	0.60	.50
K_4	.100	.150	.050	.050	.020
R^2	.8563	.7726	.8350	.8524	.7999
Par.	Optimal Values (obw=0.084)				
Ce	1.028	1.026	1.024	1.027	1.026
β	4.57	4.58	4.21	4.57	4.68
Lp	39.92	39.76	45.30	40.07	39.46
K_0	.642	.641	.651	.639	.645
K_1	.236	.228	.233	.235	.236
UZL	19.18	18.90	18.88	19.09	19.79
Lag	.586	.586	.584	.583	.588
Perc	.637	.639	.688	.636	.623
K_4	.0110	.0111	.0136	.0110	.0106
Func3	.144	8.653	.074	.075	3.501
R^2	.8563	.8562	.8549	.8561	.8569
Par.	Optimal Values (obw=0.080)				
Ce	1.012	1.020	1.026	1.016	1.023
β	4.72	4.53	4.30	4.64	4.60
Lp	38.87	40.31	42.93	39.36	39.62
K_0	.642	.640	.650	.641	.644
K_1	.218	.222	.232	.219	.237
UZL	18.54	18.56	18.89	18.64	19.78
Lag	.595	.587	.582	.591	.588
Perc	.642	.647	.667	.643	.619
K_4	.0117	.0119	.0128	.0117	.0106
Func3	55.661	28.154	.125	43.051	17.297
R^2	.8570	.8560	.8548	.8566	.8568

Table 3-8(2) The results of the ACSH in the Hushile basin (Fc=180)

No.	1	2	3	4	5
Par.	Initial Values				
Ce	1.00	1.15	1.05	0.95	1.10
β	6.0	3.0	4.0	5.0	2.0
Lp	30.0	25.0	20.0	35.0	45.0
K_0	.42	.30	.35	.45	.60
K_1	.43	.25	.35	.45	.30
UZL	20.	30.	15.	23.	25.
Lag	.70	.60	.80	.60	.40
Perc	1.00	2.00	1.50	0.60	.50
K_4	.100	.150	.050	.050	.020
R^2	.8549	.7764	.8354	.8517	.8028
Par.	Optimal Values (obw=0.084)				
Ce	1.031	1.023	1.031	1.029	1.029
β	4.05	4.57	4.12	4.181	3.95
Lp	40.82	37.63	40.29	39.97	42.58
K_0	.639	.654	.639	.640	.648
K_1	.237	.229	.223	.224	.235
UZL	19.08	19.31	18.60	18.67	19.85
Lag	.582	.588	.587	.591	.581
Perc	.682	.654	.682	.680	.615
K_4	.0133	.0110	.0131	.0129	.0106
Func3	.233	23.72	.580	4.940	.018
R^2	.8556	.8575	.8560	.8566	.8555
Par.	Optimal Values (obw=0.080)				
Ce	1.013	1.019	1.027	1.021	1.030
β	4.39	4.26	4.10	4.23	4.03
Lp	38.28	39.18	40.50	39.49	40.99
K_0	.631	.642	.642	.641	.647
K_1	.255	.220	.221	.221	.235
UZL	19.29	18.71	18.42	18.66	19.87
Lag	.590	.596	.589	.594	.584
Perc	.683	.644	.680	.681	.616
K_4	.0133	.0116	.0135	.0134	.0105
Func3	62.97	40.77	12.97	36.21	2.97
R^2	.8572	.8570	.8560	.8568	.8560

Table 3-9(1) The results of the ACSH in the Salvajina basin (Fc=300)

No.	1	2	3	4	5
Par.	Initial Values				
Ce	0.5	0.7	0.6	0.4	0.8
β	2.0	1.5	3.0	1.0	4.0
Lp	200.0	150.0	100.0	180.0	130.0
K_0	0.40	0.20	0.10	0.01	0.30
K_1	0.70	0.20	0.40	0.01	0.30
UZL	30.0	20.0	10.0	40.0	50.0
Lag	4.0	2.0	1.0	6.0	5.0
Perc	0.35	0.10	0.2	0.01	0.15
K_4	0.5	0.7	0.8	0.4	0.6
R^2	.7640	.6930	.2597	.2899	.5097
Par.	Optimal Values (obw=0.050)				
Ce	.566	.566	.566	.566	.566
β	1.0	1.0	1.0	1.0	1.0
Lp	187.36	187.34	187.43	187.40	187.36
K_0	.062	.093	.062	.092	.061
K_1	.162	.132	.162	.133	.163
UZL	44.20	14.17	44.11	14.22	44.10
Lag	.716	.680	.713	.684	.715
Perc	4.26	4.07	4.26	4.07	4.27
K_4	.0432	.0428	.0432	.0428	.0432
Func3	-34.14	-34.12	-34.25	-34.42	-34.14
R^2	.8450	.8441	.8450	.8442	.8450
Par.	Optimal Values (obw=0.045)				
Ce	.566	.567	.566	.566	.566
β	1.0	1.0	1.0	1.0	1.0
Lp	187.37	187.39	187.40	187.40	187.42
K_0	.060	.089	.093	.093	.061
K_1	.163	.137	.132	.132	.163
UZL	44.03	13.61	14.23	14.21	44.15
Lag	.716	.687	.679	.680	.714
Perc	4.26	4.25	4.07	4.07	4.27
K_4	.0432	.0437	.0428	.0428	.0432
Func3	-34.34	-34.75	-34.43	-34.40	-34.70
R^2	.8450	.8445	.8441	.8441	.8450

Table 3-9(2) The results of the ACSH in the Salvajina basin (Fc=260)

No.	1	2	3	4	5
Par.	Initial Values				
Ce	0.5	0.7	0.6	0.4	0.8
β	2.0	1.5	3.0	1.0	4.0
Lp	200.0	150.0	100.0	180.0	130.0
K_0	0.40	0.20	0.10	0.01	0.30
K_1	0.70	0.20	0.40	0.01	0.30
UZL	30.0	20.0	10.0	40.0	50.0
Lag	4.0	2.0	1.0	6.0	5.0
Perc	0.35	0.10	0.2	0.01	0.15
K_4	0.5	0.7	0.8	0.4	0.6
R^2	.7586	.6838	.2317	.2945	.4921
Par.	Optimal Values (obw=0.050)				
Ce	.564	.564	.564	.563	.564
β	1.0	1.0	1.0	1.0	1.0
Lp	167.20	166.94	167.41	167.98	166.93
K_0	.033	.069	.070	.036	.069
K_1	.151	.145	.144	.154	.145
UZL	46.41	15.02	15.02	41.71	15.00
Lag	.675	.697	.697	.679	.701
Perc	3.99	4.28	4.27	4.01	4.28
K_4	.0408	.0422	.0422	.0408	.0422
Func3	-.001	-.047	-.105	-.014	-.070
R^2	.8427	.8428	.8428	.8430	.8428
Par.	Optimal Values (obw=0.045)				
Ce	.564	.564	.564	.563	.564
β	1.0	1.0	1.0	1.0	1.0
Lp	167.22	166.96	166.94	167.02	166.94
K_0	.070	.069	.071	.068	.138
K_1	.144	.145	.144	.143	.154
UZL	15.07	15.00	15.09	14.62	41.72
Lag	.696	.699	.696	.696	.681
Perc	4.27	4.28	4.27	4.27	4.02
K_4	.0422	.0422	.0422	.0424	.0406
Func3	-.000	-.084	-.046	-.014	-.108
R^2	.8428	.8428	.8427	.8430	.8429

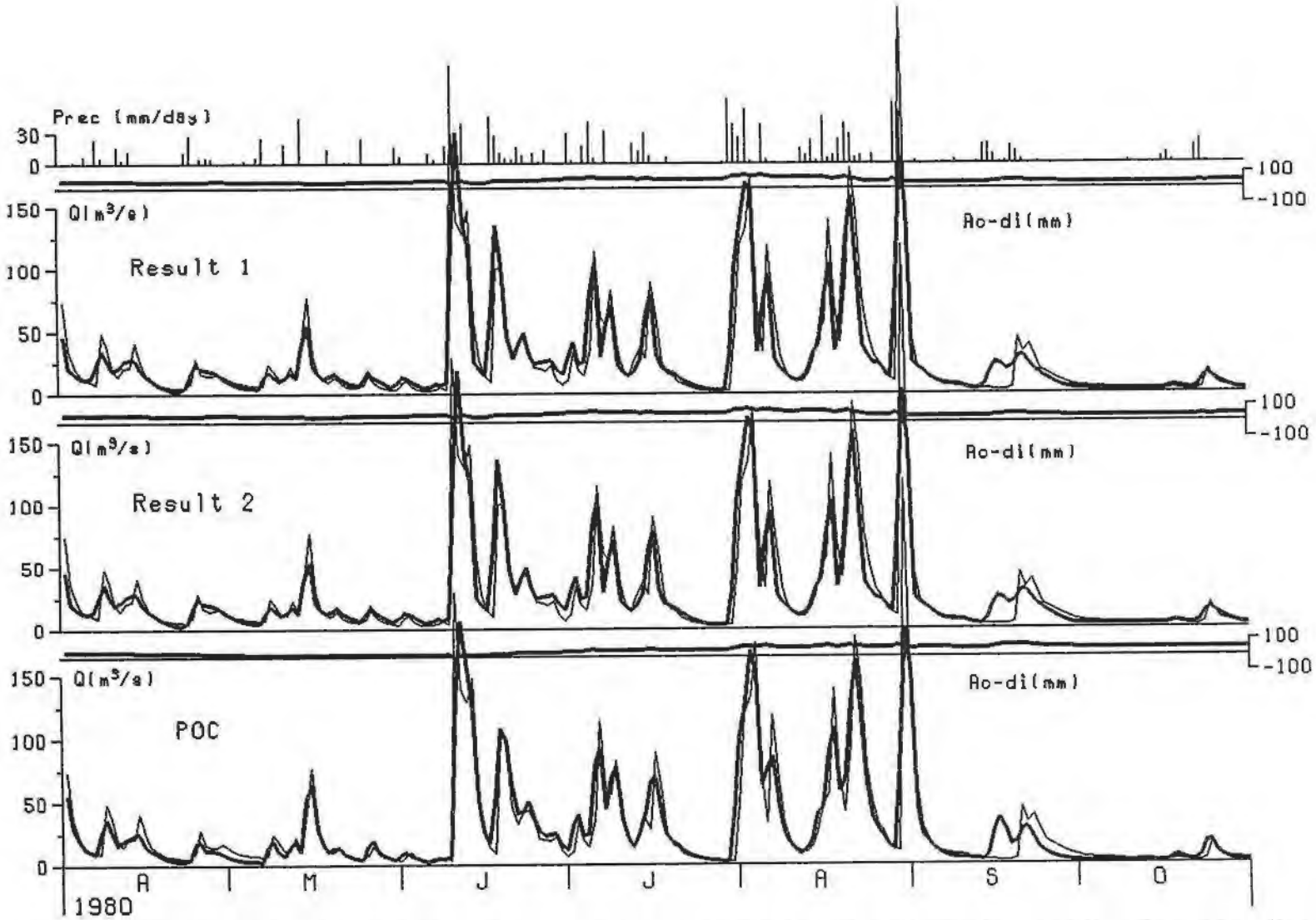

Fig. 3-2 The computed (thick lines) and observed (thin lines) hydrographs for the Hushile basin. Above: the result of ACSH with Fc=200 mm, Middle: the result of ACSH with Fc=180 mm, Below: the result of POC.

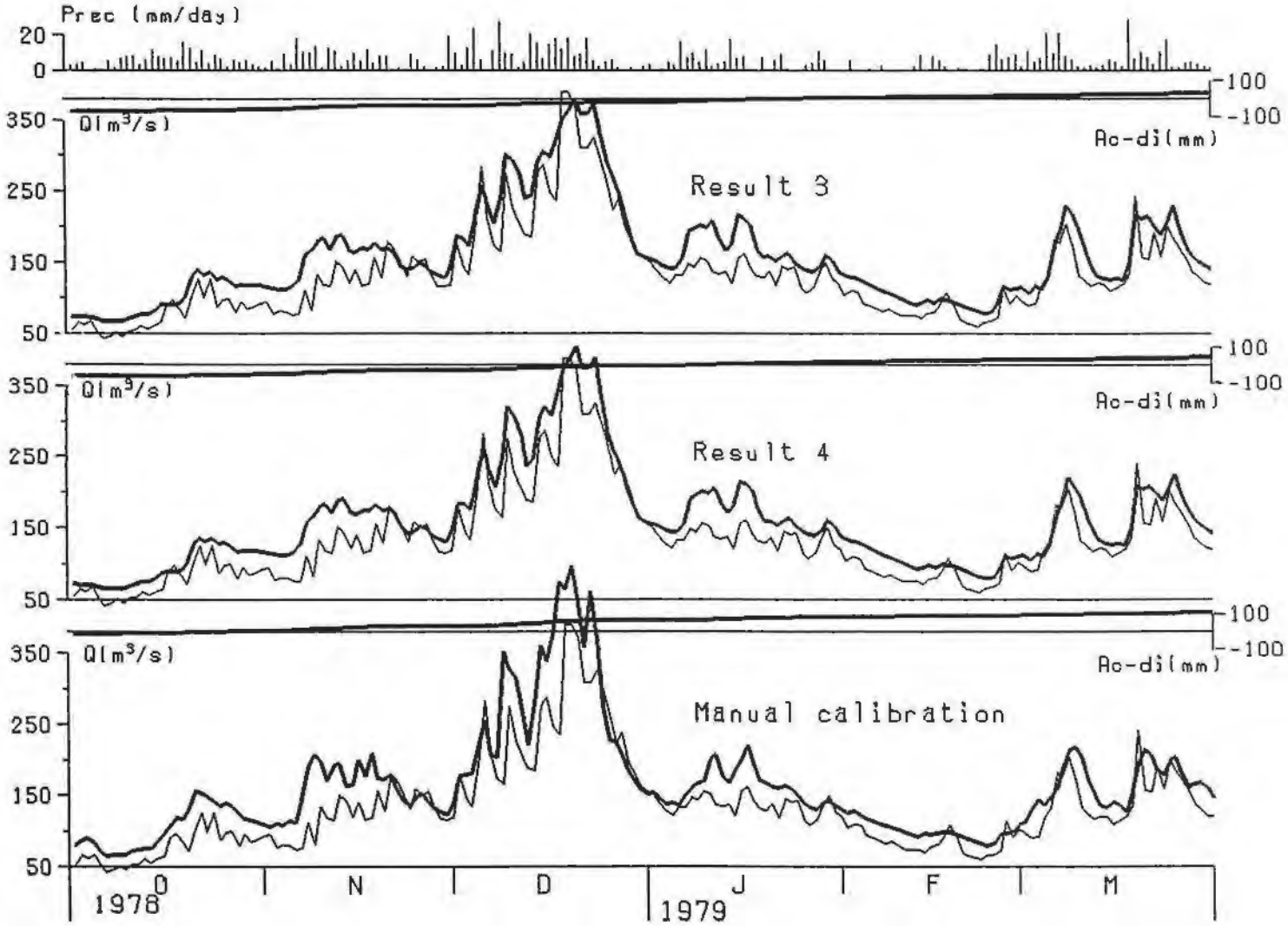

Fig. 3-3 The computed (thick lines) and observed (thin lines) hydrographs for the Salvajina basin in calibration period. Above: the result of ACSH with Fc=300 mm, Middle: the result of ACSH with Fc=260 mm, Below: the result of manual calibration.

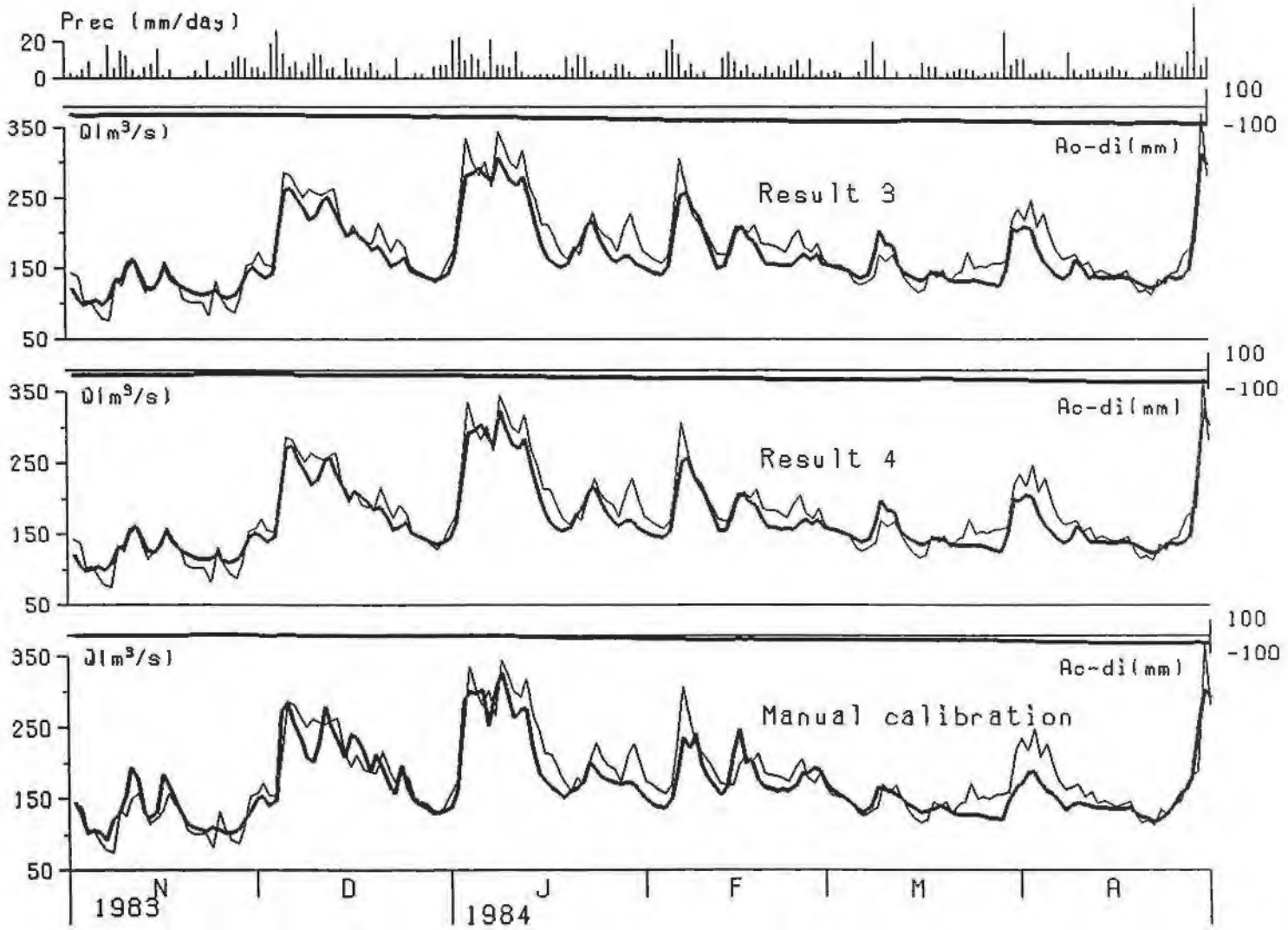

Fig. 3-4 The computed (thick lines) and observed (thin lines) hydrographs for the Salvajina basin in extrapolation period. Above: the result of ACSH with Fc=300 mm, Middle: the result of ACSH with Fc=260 mm, Below: the result of manual calibration.

6. CONCLUSIONS

The structure of the soil moisture routine was modified finely and a model parameter *Ce* was introduced into this routine in the ACSH. The parameter *Fc* should, if possible, be determined according to its physical definition before the ACSH. So, the calibrated parameters are *Ce*, β and *Lp*. They are considerably stable in the ACSH. The interference of the parameters of this routine and unrealistic values of *Fc* could be avoided in this manner.

The *func5* is an effective way to make full use of the information derived from the observed data. If there are no lakes in a basin, the first stage is independent of the second stage because of the *func5*, which means that the optimal values of the first stage are not interfered by the parameters of the second stage.

The suitable *obw* is important in the ACSH. But, it is not difficult to find a suitable value for *obw*. The splitting of the sub-periods is important too. We should pursue the splitting as correctly as possible, and also as many sub-periods as possible. There will be a little difference in the solutions with the different *Fc*. But, the small deviation will not destroy the solution of the ACSH.

The ACSH was tested in two basins. The optimal values of the parameters were reasonable and were considerably stable with the different initial values. This is one merit of the ACSH. The model with the parameter solution of the ACSH performed well in both the calibration period and the extrapolation period. So, its result could be used as a reference or an alternative solution.

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