HYDROLOGICAL PROCESSES, VOL. 11, 1671–1682 (1997)

DEVELOPMENT OF AN AUTOMATIC CALIBRATION SCHEME FOR THE HBV HYDROLOGICAL MODEL

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ABSTRACT

An automatic calibration scheme for the HBV model (ACSH) was developed. The ACSH was based on the physical significance of the model parameters and structure. The inference of hydrologists in the manual calibration was adopted as the guideline. A slight modification of the model structure of the soil routine was suggested to avoid interdependence of the parameters. In total nine parameters, except the snow routine, *Fc* and *MAXBAS*, were calibrated automatically in two stages; first the soil moisture routine and then the others. There are six sets in two stages in total. Using the Powell method, the parameters in each step were calibrated simultaneously with carefully selected objective functions, and in particular a powerful objective function for the soil moisture routine. The steps were in a fixed order in the ACSH according to the model structure. The optimal values of the model parameters were stable, with the different initial values varying in considerable ranges. The automatic calibration gave the same model performance as the manual calibration when the ACSH was tested in two basins. The automatic calibration can thus be used as a reference or as an alternative solution of the model. © 1997 John Wiley & Sons, Ltd.

Hydrol. Process., Vol. 11, 1671–1682 (1997).

(No. of Figures: 5 No. of Tables: 3 No. of Refs: 16)

KEY WORDS HBV model; parameter sets; objective functions; automatic calibration

INTRODUCTION

Over the past three decades, there have been significant developments in hydrological modelling. Hydrological models have been used as the main tool for flood forecasting, for example. An important but difficult problem in model application is the calibration of the parameters. Most of the parameters in a model are stated to have physical significance and definition. Nevertheless, it is very difficult to determine their values according to these definitions. These parameters, coupled with the free parameters, are calibrated on the basis of the observed discharge only. Manual calibration is usually considered the most realistic way. However, this is a tedious procedure and requires extensive knowledge about the model structure and parameters. Different results are obtained by different hydrologists, and the quality of calibration is often closely related to the skill and knowledge of the hydrologist. For these reasons automatic calibration schemes have been pursued; for example, by Bergström (1976), Sugawara (1979), Sorooshian and Dracup (1980), Sorooshian and Gupta (1983), Gupta and Sorooshian (1985), Zhang (1988), Brazil (1989) and Harlin (1991). It is, however, very difficult to develop a successful scheme, although many developers claim that their schemes perform well in practical applications.

It has been demonstrated that a successful optimization scheme for a hydrological model cannot rely on the careful design of the automatic optimization method only. In fact, the biggest impediments are the interdependence of the parameters and the dependence of the optimal values on their initial values.

The HBV hydrological model (Figure 1) was designed in the Swedish Meteorological and Hydrological Institute (Bergström, 1976, 1992). An automatic calibration scheme (POC) was developed for the HBV model by Harlin (1991). In this paper, this work is continued, and a new scheme, ACSH (an automatic calibration scheme for the HBV model), developed. In the scheme, some changes in the model structure were

CCC 0885–6087/97/121671–12$17·50

Received 3 August 1995
Accepted 30 September 1996

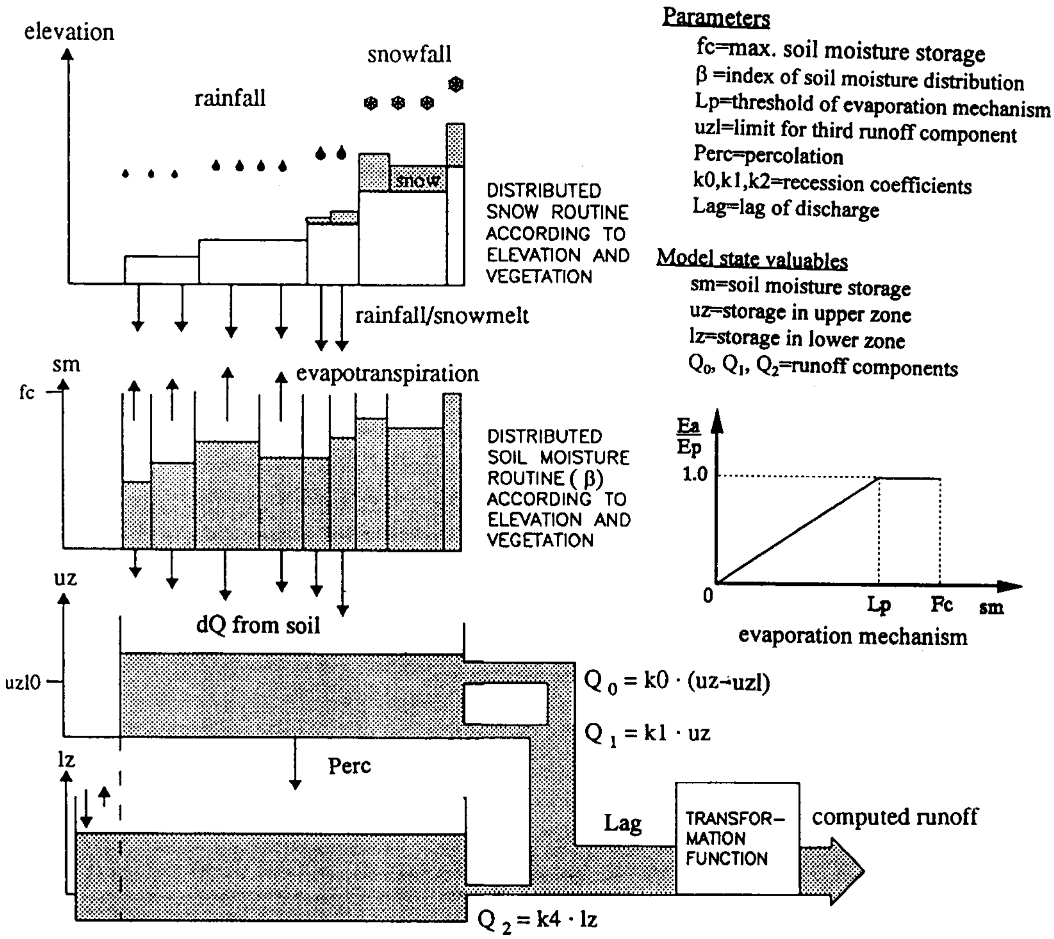

Figure 1. The general structure of the HBV model as applied to one sub-basin

suggested, alternative objective functions were adopted and ways of accounting for the interdependence of some model parameters were designed. The scheme (ACSH) has been evaluated in two basins.

HBV MODEL STRUCTURE AND CALIBRATED PARAMETERS

The HBV model is a conceptual hydrological model (Figure 1) and has been applied successfully in some 30 countries world-wide (Bergström, 1976, 1992). It was originally developed for use in Scandinavian catchments but has proven to run well in tropical and subtropical areas as well; see, for example, Bathia *et al.* (1984) and Häggström *et al.* (1990). For most applications the model is run on daily values of rainfall and temperature and monthly estimates of potential evapotranspiration. It consists of routines for snow accumulation and melt, soil moisture accounting, runoff response and, finally a routing procedure. The model can be used in a distributed mode by dividing the basin into sub-basins. Each sub-basin is then divided into zones according to altitude, lake area and vegetation.

The soil moisture routine is based on three empirical parameters: β, Fc and Lp, as shown in Figure 1. β controls the contribution (dQ) to the runoff response routing and the increase ($1 - dQ$) in soil moisture storage (sm). Fc is the maximum soil moisture storage in the model. The relationship of these parameters is given by $dQ/dP = (sm/Fc)^{\beta}$, where P is precipitation. Lp is the value of the soil moisture, above which evapotranspiration (Ea) reaches its potential level (Ep). Since mass balance over the soil is given by: $dQ = dP - dsm$, soil moisture accounting can be expressed as $dsm/dP = 1 - (sm/Fc)^{\beta}$. The parameters of Fc, Lp and β are included in the calibration.

Excess water from the soil is transformed by the runoff response function. This routing consists of two tanks that distribute the generated runoff in time, so that the quick and slow parts of the recession are obtained (Figure 1). The lower tank is a simple linear reservoir representing contribution to baseflow. It also includes the effects of direct precipitation and evaporation over open water bodies in the basin. The lower tank storage (lz) is filled by percolation from the upper tank ($Perc$), and k_4 is the recession coefficient. If the yield (dQ) from the soil moisture routine exceeds the percolation capacity, the upper tank will start to fill. Upper tank storage (uz) is drained by two recession coefficients, k_0 and k_1, separated by a threshold (uzl). This tank models the response at flood periods. Parameters calibrated from the runoff response function are $Perc, k_0$, k_1, k_4 and uzl. Finally, runoff is computed independently for each sub-basin by adding the contribution from the upper and the lower tanks. In order to account for the damping of the flood pulse in the river before reaching the basin outlet, a simple routing transformation is made. This filter has a triangular distribution of weights with the base length, $MAXBAS$ and a time retaining Lag. $MAXBAS$ and Lag are parameters.

When the model is used in a region without snow, the snow accumulation and melt routine can be ignored in the model. $MAXBAS$ is an integral parameter and can be calibrated easily and is not studied in this paper. So, in total nine parameters (Fc, β, Lp, k_0, k_1, UZL, Lag, $Perc$ and k_4) were included in the ACSH.

OBJECTIVE FUNCTIONS

A suitable objective function is one of the keys for a successful scheme. Different kinds of objective functions lay particular stress on the different features of the simulation. We should therefore search for a powerful objective function for a parameter, or a set of parameters individually.

Usually, an objective function is constructed for a whole calibration period. The water balance in some subperiods, however, is also very useful information because one specific process (i.e. some special parameters) dominates the runoff in a special subperiod. For example, evaporation is dominated by Ep only when soil moisture storage, sm, is larger than Lp in the HBV model, β will lose its effect on runoff yield when sm reaches Fc. So, it is appropriate to split the whole calibration period into subperiods. It is helpful to reduce the interference between the parameters. Harlin (1991) split the hydrological year into four subperiods; rain, baseflow, snowmelt and rain flood periods used in the POC. In this paper, the whole period is split into many more subperiods than that of Harlin's method. Supposing, there is a calibration period (n time steps) as shown in Figure 2, it could be divided into three subperiods. The subperiod time steps are n_1, n_2 and n_3, and

$$n = \sum_{l=1}^{m} n_l$$

where $m = 3$ is the number of subperiods. This kind of splitting has been used successfully by Zhang (1988). The principle of the splitting is to make the runoff correspond to the rainfall in a subperiod. We should try to make the splitting as correct as possible, and also use as many subperiods as possible.

The objective functions adopted in the ACSH are listed below. Some of them are constructed in the whole calibration period, and some others are in the subperiods (Figure 2).

$$func1 = \sum_{j=1}^{n} (Q_c(j) - Q_o(j))^2 \tag{1}$$

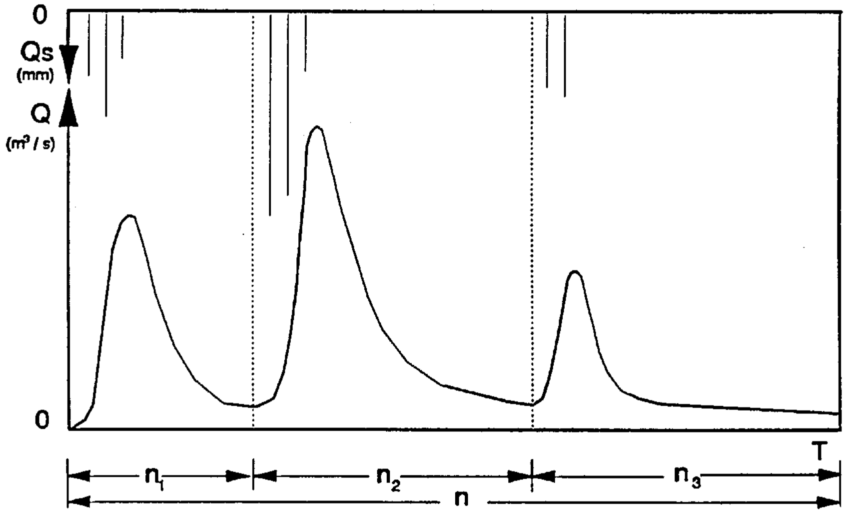

Figure 2. The example of flood events, where Q is the observed discharge, Qs is the calculated runoff or net precipitation, n is the number of time steps in the whole calibration period. In this example, the period is split into three subperiods; the time steps are n_1, n_2 and n_3. In each subperiod, Qs corresponds to its flood event

where $Q_c(j)$ =calculated discharge, $Q_o(j)$ =observed discharge and *func*1 is the sum of square errors in the whole calibration period. This function is a general description of the modelling and all the model parameters will affect it.

$$func2 = \sum_{j=1}^{n}\left[(Q_s(j) - Q_o(j))\right] \tag{2}$$

where $Q_s(j)$ is the calculated runoff, or is referred to as net precipitation. *func*2 is the absolute accumulated volume error over the whole period. Only the runoff yield process is considered in this function, so it could be used to calibrate the parameters that dominate the runoff yield.

$$func3 = \sum_{l=1}^{m}\left[\sum_{j=1}^{n_l}(Q_s(j) - Q_o(j))\right] \tag{3}$$

*func*3 equals the sum of *func*2 in each subperiod. The water balances in each subperiod are counted and the effects of the parameters that are active in only a part of the periods are emphasized.

$$func4 = func3 + obw * func2 \tag{4}$$

*func*4 is a mixture of *func*2 and *func*3. The accumulated volume errors could be balanced between the whole period and subperiods by the weight *obw*.

In the HBV model, if the evapotranspiration from the lower zone is neglected, *func*2, *func*3 and *func*4 depend only on the parameters of the soil moisture routine. So these functions could be used specially for the parameters of this routine.

$$func5 = \sum_{j=1}^{n}\left[(Q_c(j) - Q_o(j)) * Q_o(j)\right] \tag{5}$$

In *func*5, the modelling error of the discharge is weighted by the discharge of this time step, and the flood peak agreement is enhanced. This function is powerful for the parameters that dominate the flood peak (Zhang, 1988), such as *uzl* and k_0 in the HBV model.

$$func6 = \sum_{j=1}^{n} \left[\log Q_c(j) - \log Q_o(j) \right] \quad (6)$$

In *func*6, the logarithmic discharge is adopted, so, the error of the modelling discharge with the larger discharge values is reduced, i.e. the baseflow agreement is enhanced (Zhang, 1988). This function could be used for the parameters that dominate the baseflow, such as *Perc* and k_4 in the HBV model.

TEST RUNS

In order to support the scheme design, numerous automatic calibration tests were undertaken. In each test, a few parameters were calibrated with different objective functions. When these parameters were calibrated, all other parameters were used as constants. In this way, the relationship between these few parameters and their special contribution to the modelling could be revealed early, and then these parameters could be put into the scheme in a suitable position. In the tests, the different subjective initial values were inspected to identify the optimal values in order to select the parameters that could be calibrated at the same time. The results of the test runs have been adopted as the foundation of the design of the ACSH.

All the tests were run in the Hushile basin. Hushile is located in the middle eastern region of the PR of China and covers an area of about 492 km^2. The mean annual precipitation (1980–1985) is about 1740 mm and the mean annual runoff is about 1030 mm. There are six rain gauges, and one evaporation observation station. Daily discharge data at the outlet of the basin were available. The tests were run for the period 1980–1985.

Table I gives an example of the tests. In this example, three parameters were calibrated simultaneously, five initial values sets and two objective functions were inspected. R^2 is the efficiency criterion (Nash and Sutcliffe, 1970). A full description of these tests is given by Zhang (1994). To summarize, we can draw the following conclusions.

1. It is difficult to calibrate all the parameters simultaneously because of their interdependence, especially *Fc*, β and *Lp*.

2. In numerous tests, it was found that there is a close relationship between the optimal values of *Fc* and β (Figure 3). The interdependence between optimized values of β and *Fc* is not surprising because of the model structure. The units of *Fc* in Figure 3 are mm and β is an exponent in the HBV. However, values of 25 are not reasonable for β and similarly 800 mm is not reasonable for *Fc*. However, it is very interesting that there is an approximate linear relationship between these two parameters. Furthermore, these optimal value sets give almost the same model performance. This means that it is difficult to calibrate these two parameters simultaneously in a scheme. But, if one of them has been determined, the other could be considered stable.

3. A slight modification of the model structure was tried, in which a parameter, *Ce*, was introduced into the soil moisture routine. The potential evaporation rate was multiplied by the factor *Ce*. When the parameters *Ce*, β and *Lp* were calibrated simultaneously, the optimal values of each parameter were stable.

4. *func*4 is a combination of *func*2 and *func*3. With an increase in *obw*, *func*2 will dominate *func*3 and the absolute accumulated volume error in the whole period can be absolutely eliminated. However, the stability of the optimal parameter values will decrease. Conversely, they can be quite stable, but the error in the whole period could be considerable. So, a suitable *obw* is important. It was found that a suitable *obw* could be found and that *func*4 is a powerful function for the soil moisture routine.

Table I. An example of the tests. *Lp* is the relative value of soil moisture to *Fc*. *Fc*, β and *Lp* are the parameters to be calibrated, and all other model parameters are used as constants in this test. R^2 is the efficiency criterion. The first part of the table is the initial values of the calibrated parameters and there are five sets in total. Using *func*1 and *func*3 as the objective functions, the second and third parts of the table are the optimal parameter values corresponding to the initial values. Lines *func*1 and *func*3 are the optimal values of the objective functions

No.	1	2	3	4	5
Parameter					
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	0·8621	0·8604	0·8589	0·8636	0·8528
Optimal values with *func*1					
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
func	366 194	367 848	366 199	366 199	366 209
R^2	0·8642	0·8636	0·8642	0·8642	0·8642
Optimal values with *func*3					
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
func	2685·4	2353·0	2740·77	2421·9	2746·1
R^2	0·8580	0·8569	0·8584	0·8549	0·8584

5. The interdependence between the parameters, except those of the soil moisture routine, is not so strong. Some specific objective functions are evidently efficient for some parameters, such as, *func*5 for k_0, *uzl* and *Lag*, and *func*6 for k_4 and *Perc*.

6. The response surface of an objective function is something like a rolling terrain area (cf. Duan, 1992). There are some local low points, but only one global lowest point in a surface. The complex nature of the surface and the number of the local lowest points are dependant on the number of the parameters calibrated and the structure of the objective function. The autocalibration searches for the global lowest point. By trying enough random initial values, it is possible to find the global lowest point. For the HBV model, this method is powerful, using the objective functions addressed above.

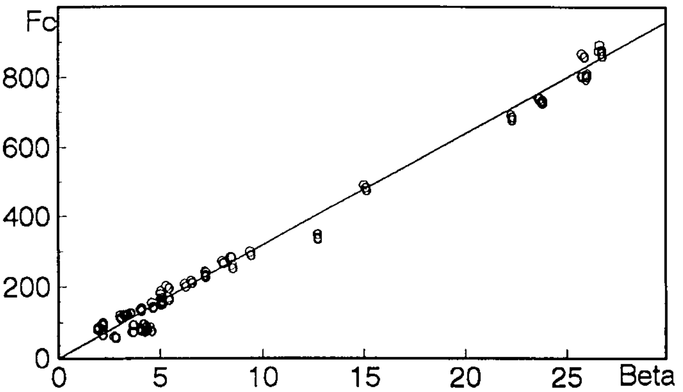

Figure 3. The relationship of the optimum values of *Fc* and β for the tests. The values were derived from different tests, including different parameter combinations with the different objective functions and initial values. There are about 60 points in the figure in total. *Fc* in mm

AUTOMATIC CALIBRATION SCHEME FOR THE HBV MODEL

On the basis of the tests mentioned above, the ACSH was designed. Now the methodology of the ACSH is described. A total of nine parameters (except the snow routine, *Fc* and *MAXBAS*) were calibrated in two stages; first, the soil moisture routine and then the remaining ones. In the first stage, a parameter *Ce* was introduced and the parameters were calibrated in two steps. In the second stage, the remaining parameters were calibrated in four steps with different objective functions. The automatic optimization method adopted in the ACSH was that of Powell (William *et al*., 1992).

First stage

It is evident from Figure 3 that there is a close relationship between optimal values of *Fc* and β and that it is very difficult to calibrate them simultaneously in a scheme. This relationship is in line with experience from manual calibration. The parameter *Fc* expresses the tension soil moisture capacity of a basin. It should be possible to estimate its value according to the climatic, geological, geographical and hydrological conditions of a basin before the model calibration. A lot of experience has been gained regarding the validation of *Fc* from model applications. Therefore, *Fc* is fixed before the automatic calibration in the ACSH, in order to get stable and reasonable solutions of β and also to eliminate the interaction between *Fc* and *Lp*. When *Fc* is pre-fixed, it will be inoperative as a parameter. So, a parameter *Ce* was introduced in the ACSH. The introduction of *Ce* is one core of this initial stage.

The first step of this stage was to calibrate *Ce*, β and *Lp* simultaneously with fixed *Fc*. The objective function was *func*4. Around an initial value set selected by the user, 10 other random initial value sets were tried automatically. Owing to interference, these optimal values could not converge absolutely. However, they were all located in reasonably small ranges, and the arithmetic average of the optimal values of β were considerably stable. Hence, only β was fixed at the average value at this step. According to the tests, the eleven sets were enough to get a stable average of β.

The second step was to calibrate *Ce* and *Lp* again with the condition of fixed *Fc* and β. *func*4 was still adopted as the objective function. Eight other initial value sets were tried automatically. The optimal values in this step were much more stable than those in the first step. These two parameters were fixed at one optimal value set with the minimum objective function value of the nine sets. Because *func*4 was used in this stage, the calibration will not be influenced by the other parameters.

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 *func*1. As in the first stage, several other initial value sets were inspected automatically. According to the tests, the optimal values of this step were reasonably 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 main foundation of this stage.

*func*1 is not the only measurement of model performance. In fact, in manual calibration, specialists inspect the agreements of the different parts of the hydrograph, and then adjust the corresponding parameters. The following three steps were therefore designed in the ACSH.

The second step was to calibrate the parameters k_0, *uzl* and *Lag* simultaneously with *func*5. The other three parameters used the results from 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 *func*6. 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 baseflow agreement. The fourth step was to calibrate k_1 only with *func*1. The remaining parameters used their optimal values from the second step or the third step. After the second and third steps, it is necessary to readjust k_1.

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

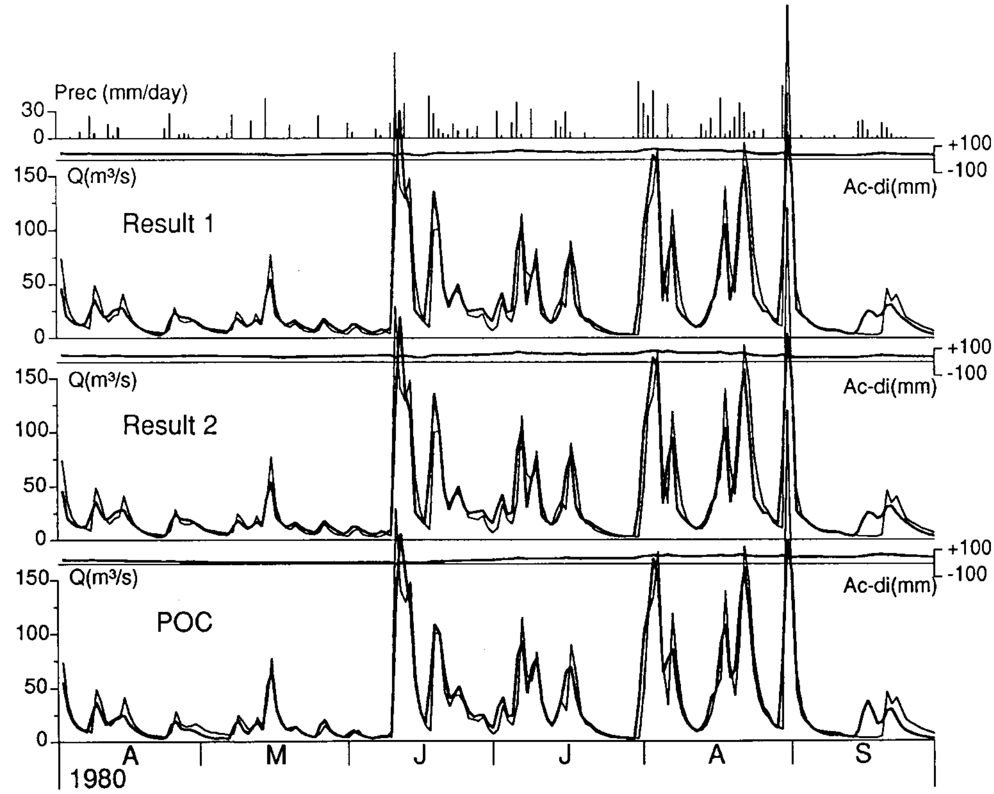

Figure 4. The computed (thick lines) and observed (thin lines) hydrographs for the Hushile basin. Top: (result 1, corresponding to result no. 5 in Table II): the result of the ACSH with $Fc = 200$ mm and $obw = 0{\cdot}084$; middle (result 2): the result of the ACSH with $Fc = 180$ mm and $obw = 0{\cdot}084$; bottom (POC): the result of the POC. Q is discharge, *Prec* is precipitation and *Ac-di* is the accumulative value error of the computed and observed runoff. The period is from April to September 1980

After the last three steps, R^2 decreased slightly. However, the result will be more realistic because these steps were designed on the basis of the effects of the parameters.

In summary, there are six steps in the ACSH.

Step 1. The parameters *Ce*, β and *Lp* are calibrated with *func*4, but only β was fixed.

Step 2. The parameters *Ce* and *Lp* are calibrated and fixed with *func*4.

Step 3. The parameters k_0, k_1, *uzl*, *Perc*, k_4 and *Lag* are calibrated with *func*1 to get good initial estimates for steps 4–6.

Step 4. The parameters k_0, *uzl* and *Lag* are calibrated and fixed with *func*5.

Step 5. The parameters k_4 and *Perc* are calibrated and fixed with *func*6.

Step 6. The parameter k_1 is calibrated and fixed with *func*1.

In the ACSH, only some of the parameters of the HBV model were considered.

EVALUATION OF THE ACSH IN TWO BASINS

The ACSH has been tested in two basins, the Hushile basin and the Salvajina basin. The details of the Hushile basin have been described above. The Salvajina basin is located in the upper reach of the Rio Cauca,

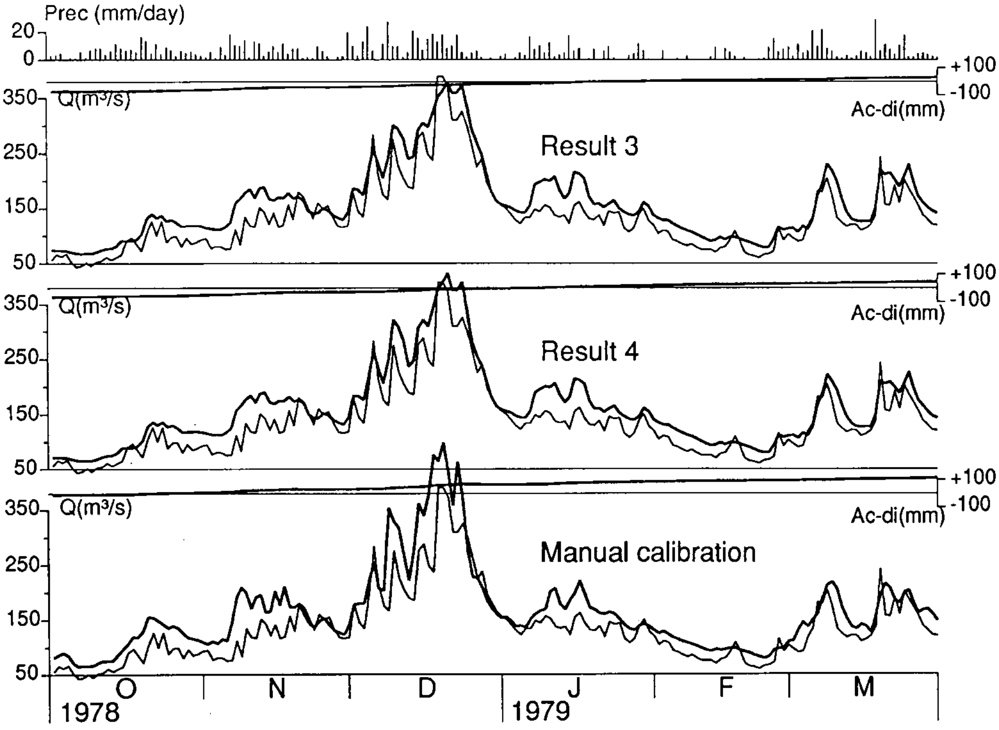

Figure 5. The computed (thick lines) and observed (thin lines) hydrographs for the Salvajina basin. Top: (result 3, corresponding to result no. 5 in Table III): the result of the ACSH with $Fc = 300$ mm and $obw = 0{\cdot}050$; middle (result 4): the result of the ACSH with $Fc = 260$ mm and $obw = 0{\cdot}050$; bottom (manual calibration): the result of the manual calibration (Häggström *et al.*, 1988). *Q* is discharge, *Prec* is precipitation and *Ac-di* is the accumulative value error of the computed and observed runoff. The period is from October 1978 to March 1979

Colombia, and covers an area of 3652 km^2. This region is located within the zone that is influenced by intertropical convergence with high precipitation and no snow. Floods are caused by long periods of rain and not by occasional rain storms. This hydrological regime is clearly different from that in the Hushile basin. The observed data (precipitation, potential evaporation and discharge) were available for a total of 10 years (1975–1984). These two basins are very different in their physical characteristics, locations and hydrograph responses (Figures 4 and 5).

The evaluations were undertaken in the calibration periods 1980–1985 in Hushile, and 1975–1982 in Salvajina. The calibration periods were divided into 43 and 38 subperiods, respectively. Furthermore, in the Salvajina basin, the result was verified in an extrapolation period from 1983 to 1984. In both basins, different *Fc* and *obw* were tested in order to identify their effect on the results. Detailed discussion of certain of the results is given in Zhang (1994).

RESULTS AND DISCUSSION

Stability with the different initial values is a most important characteristic of an automatic calibration scheme. In Tables II and III, it is evident that the optimal values of the parameters are stable. Every optimal parameter set in the tables could be adopted as the solution.

Comparing the POC in Hushile, there were some differences in optimal parameter values (Zhang, 1994), but they were all within reasonable limits. In hydrograph modelling, the R^2 of the ACSH was higher than that of the POC. The important point is that the optimal parameter values of the ACSH were stable, but those of the POC were slightly dependent on the initial values.

Table II. The results of the ACSH in the Hushile basin with $Fc = 200$ mm, $obw = 0{\cdot}084$. Ce, β, Lp, k_0, k_1, uzl, Lag, $Perc$ and k_4 are the calibrated parameters. Lp is the absolute value of soil moisture (in mm). The first part of the table gives the five initial value sets, the second part gives the optimal parameter values corresponding to the initial values. Line *Func*3 is the value of objective function *func*3; it is an expression of the modelling of the runoff volume

No.	1	2	3	4	5
Parameter					
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	0·42	0·30	0·35	0·45	0·60
k_1	0·43	0·25	0·35	0·45	0·30
uzl	20·0	30·0	15·0	23·0	25·0
Lag	0·70	0·60	0·80	0·60	0·40
$Perc$	1·00	2·00	1·50	0·60	0·50
k_4	0·100	0·150	0·050	0·050	0·020
R^2	0·8563	0·7726	0·8350	0·8524	0·7999
Optimal values					
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	0·642	0·641	0·651	0·639	0·645
k_4	0·236	0·228	0·233	0·235	0·236
uzl	19·18	18·90	18·88	19·09	19·79
Lag	0·586	0·586	0·584	0·583	0·588
$Perc$	0·637	0·639	0·688	0·636	0·623
k_4	0·0110	0·0111	0·0136	0·0110	0·0106
*Func*3	0·144	8·653	0·074	0·075	3·501
R^2	0·8563	0·8562	0·8549	0·8561	0·8569

In Salvajina, the R^2 of results 3 and 4 (Figure 5) were both 0·84 in calibration period. When they were verified in the extrapolation period, the R^2 were 0·90 and 0·91 (They are much higher than that in the calibration period, which means that the ACSH may be a good basis for extrapolation). As far as manual calibration is concerned (Häggström *et al*., 1988), the R^2 were 0·78 in the calibration period and 0·69 in the extrapolation period.

It is important to search for a suitable *obw* value in the ACSH. Several were tested between 0·080 and 0·084 in the Hushile basin and 0·045 and 0·050 in the Salvajina basin. There was no distinct difference between the results of the ACSH, which means that any value in these districts could be adopted in the ACSH. So, it is not difficult to select a suitable *obw*.

There were some differences between the optimum values with different Fc because of the interactions between Fc and the other three parameters in the soil moisture routine. The differences were, however, not unduly large, and the results gave almost the same model performance according to R^2 and the hydrographs. For example, the hydrographs corresponding to result 1 ($Fc = 200$) and result 2 ($Fc = 180$) in Figure 4 are nearly the same, as are the corresponding R^2. The small deviation of Fc will not detract from the reasonableness of the solution of the ACSH.

It is true that there is subjectivity in subperiod splitting. As mentioned above, the splitting principle is to ensure that runoff corresponds to the rainfall in a subperiod and to make as many subperiods as possible. When there are enough subperiods, such as used in this paper, a few subperiods more or less will not influence the results. In the ACSH, the first few subperiods are excluded from the process of calculating the value of an objective function, which means that these subperiods are used as the 'preheat' period. Thereby, the starting values of the state variables of the model should not influence the results.

Table III. The results of the ACSH in the Salvajina basin with $Fc = 300$ mm, $obw = 0{\cdot}050$. Ce, β, Lp, k_0, k_1, uzl, Lag, $Perc$ and k_4 are the calibrated parameters. Lp is the absolute value of soil moisture in mm. The first part of the table gives the five initial value sets, the second part the optimal parameter values corresponding to the initial values. Line *func*3 is the value of objective function *func*3 and is an expression of the modelling of the runoff volume

No.	1	2	3	4	5
Parameter					
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	0·7640	0·6930	0·2597	0·2899	0·5097
Optimal values					
Ce	0·566	0·566	0·566	0·566	0·566
β	1·0	1·0	1·0	1·0	1·0
Lp	187·36	187·34	187·43	187·40	187·36
k_0	0·062	0·093	0·062	0·092	0·061
k_1	0·162	0·132	0·162	0·133	0·163
uzl	44·20	14·17	44·11	14·22	44·10
Lag	0·716	0·680	0·713	0·684	0·715
$Perc$	4·26	4·07	4·26	4·07	4·27
k_4	0·0432	0·0428	0·0432	0·0428	0·0432
*func*3	−34·14	−34·12	−34·25	−34·42	−34·14
R^2	0·8450	0·8441	0·8450	0·8442	0·8450

In the Salvajina basin, the parameter β converged at about 0·6 if there was no restriction. This value is not reasonable, although the model performs even better with this value than in the present solution. Accordingly, β was restricted to be no less than 1 on the basis of its physical definition (Bergström, 1976). In this case, β always reached its lower boundary in the ACSH. Thus, if we want to get a reasonable result of β without the restriction, both the scheme and the model structure should perhaps be refined. In the Salvajina basin, it was clear that the parameters k_0 and uzl converged to two points. This is because k_0 and uzl interfere with each other. There is, however, no evident difference in R^2 and the hydrographs.

Steps 4–6 are the recalibration for the parameters k_0, uzl, Lag, k_4, $Perc$ and k_1. The objective functions adopted in these steps were selected according to the effects of the corresponding parameters in the model. The agreements in some special parts of the hydrographs, such as flood peak, are much better after step 6 than step 3 (Zhang, 1994). Comparing R^2 after the third step and the sixth step, it was reduced by only about 0·006 in the Hushile basin and 0·0004 in the Salvajina basin.

CONCLUSIONS

The ACSH is a powerful scheme. Its solution is reasonable and realistic. In particular the optimal values are particularly stable with different initial values, which is its major advantage over the POC scheme. The modelling accuracy of the ACSH is higher than that of the manual calibration. The scheme performed well in two test basins. Its results could be used as a reference or an alternative solution in practice.

By fixing *Fc* before the ACSH, and introducing *Ce*, it was possible to reduce the interference between *Ce*, β and *Lp* and to calibrate them simultaneously in a scheme. The results of the ACSH depend slightly on the chosen *Fc*, but the differences are very small. *func*4 is a powerful objective function that makes full use of the runoff volume information. The calibration for the parameters of the soil moisture routine could be separated from that of the other routines by use of *func*4. A suitable *obw* is important in the ACSH. It is, however, not difficult to determine. There is subjectivity in subperiod splitting, but such splitting will not dominate the result of the scheme when there are enough subperiods. Finally, the 'preheat' period could eliminate the effect of the start-up values of the state variables of the model.

ACKNOWLEDGEMENTS

This paper is the result of Dr Zhang's research at the Swedish Meteorological and Hydrological Institute (SMHI). The visit was made possible by a grant from the Swedish Institute. The work was also supported financially by the Swedish Association of River Regulation Enterprises (VASO) and the SMHI. The suggestions and advice of our colleagues, both at the SMHI and elsewhere, is gratefully acknowledged. Special thanks are due to Professor Sten Bergström and Dr Joakim Harlin.

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