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Regionalisation of parameters for a conceptual rainfall-runoff model

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Abstract

The HBV model, a conceptual rainfall-runoff model, was applied to 11 catchments within the NOPEX area. The catchment areas ranged from 7 to 950 km^2 with between 41 and 87% covered by forest. The aim was to relate the different model parameters to physical catchment characteristics. Such relationships would allow simulating runoff from ungauged catchments and could be used to discuss the physical basis of the model. Using a 9-year calibration period the best parameter sets were determined for each catchment. A Monte Carlo procedure and two different criteria were used for the optimisation: the common efficiency and a fuzzy measure that combined different objective functions and was found to reduce parameter uncertainty. The runoff simulations of the model agreed well with the observed runoff series and relationships to catchment characteristics could be found for six of the 13 parameters. The goodness of runoff predictions using derived regional parameter sets was tested with variable results. Some relationships between lake percentage and soil parameters called the physical basis of the model into question as they could not be explained by the physical processes in the soil but by the dominating effect of lakes to runoff variations. On the other hand, relationships between forest percentage and snow parameters supported the physical basis of the model. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The availability of hydrological measurement data is restricted in both temporal and spatial respects. Therefore, for many practical problems extension of existing data is an important task in hydrology. One possible method is the use of conceptual rainfall-runoff models. However, in such models most parameters are not measurable but have to be estimated by calibration using at least some observed runoff data. The extension of runoff series in time by the use of models is rather straightforward. On the other hand, extension in space, i.e., regionalisation of conceptual rainfall-runoff models, is more difficult. The typical approach is to look for relationships between optimised parameter values and catchment characteristics. Parameter sets can then be compiled for ungauged catchments from measurable variables. During the past decades this approach has been tested by several scientists with varying success.

Hughes (1989) used 33 catchments within 10 different regions in South Africa and the United States of

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America ranging from arid areas to temperate areas with snow cover during winter for the estimation of parameters in an event based model. He used 13 physical catchment variables and was able to establish linear relationships between most of the 12 model parameters and combinations of two to five of the 13 catchment characteristics. Servat and Dezetter (1993) applied two different lumped, conceptual models (seven and three parameters, respectively) to 20 catchments in north-western Ivory Coast. The catchments exhibit a single annual hydrograph peak and to increase the number of calibrated parameter sets the authors chose to calibrate the models year by year, a procedure that gave 91 parameter sets calibrated on 1-year series. Since they did not find any linear relationship between model parameters and catchment characteristics they tried with some success to derive multiple regression equations ($r^2 = 0.11$–0.89), where land use and yearly rainfall variables explained model parameter values best. Using 24 catchments in Northern Belgium Vandewiele et al. (1991) found high correlations between the three model parameters and the percentage of the catchment with a permeable subsurface, in one case combined with the mean precipitation. Another monthly water balance model was applied by Ibrahim and Cordery (1995) to 18 catchments in New South Wales, Australia, with annual rainfall varying from 600 to 2400 mm. Three of the four parameters could be related to catchment characteristics. All of them were found to be strongly correlated with the mean annual rainfall, whereas their correlation with other catchment characteristics was weaker. James (1972) reports a study of Ross (1970) who applied a version of the Stanford Watershed model (Crawford and Linsley, 1966) (Kentucky watershed model) to 16 rural catchments in Kentucky. He related parameter values to derived catchment characteristics such as estimated plant available water capacity (AWC) and permeability of the soil (A horizon) and found high correlations between these variables and their counterparts in the model. Results were not similarly successful in a following study with the same model (Magette et al., 1976), where attempts to find linear relationships were 'totally unsuccessful'. However, Magette et al. (1976) using 16 catchments were able to derive multiple linear regression equations for the six non-measurable model parameters. They used up to six of 15 catchment characteristics and, in some equations, other model parameters (multiple regression coefficients 0.80–0.95).

A general problem in the regionalisation of model parameters is the limited number of catchments usually available. Obviously, using larger regions increases the number of available gauged catchments. However, at the same time the variation of climate and physiography between the catchments increases as the sampling area increases, i.e., more variables have to be included into the regression analysis. Furthermore, some scatter may be introduced as relationships may change between regions (e.g., Mimikou, 1984). Runoff depends on the aggregation of many climatic, geological and physiographic conditions in a catchment. These aggregations change between catchment in different respects and, thus, it may be difficult to find relationships between model parameters and a few catchment characteristics. Another problem of regionalisation is that model parameters often are badly defined, i.e., almost equally good simulations can be obtained at very different locations in the parameter space (e.g., Seibert, 1997a; Beven and Binley, 1992; Jakeman and Hornberger, 1993). This parameter uncertainty may cause scatter in the relationships and prevent them from being detected. Furthermore, there is a risk for bias in the model calibration. This risk is obvious for manual calibration, because the modeller may search the optimal parameters influenced by what he expects. Using automatic calibration procedures different parameter sets may be found dependent on, for instance, start values of the parameter search (e.g., Kite and Kouwen, 1992).

Contrary to most of the studies mentioned above, this study concentrates on a relatively small, geographically fairly homogeneous region and, therefore, only 11 catchments were included. The aim was to apply a conceptual rainfall-runoff model, the HBV model (Bergström, 1976), to catchments within the NOPEX area (Halldin et al., 1999) and to find relationships between parameter values and catchment characteristics. The existence of such relationships would allow to regionalise the model, i.e., to provide a regional parameter set where parameter values vary with measurable catchment characteristics. Such sets could be used to simulate ungauged catchments within the region. Furthermore, relating parameters to catchment characteristics makes it possible to discuss the physical basis of a model. Some relationships can be expected from physical reasoning.

Consequently, the existence of these relationships with objectively optimised parameters would support the physical basis of the model. For the HBV model relationships between model parameters and catchment characteristics have been studied by Braun and Renner (1992) and Johansson (1994). Braun and Renner (1992) applied the model to five catchments in different parts of Switzerland and concluded that there were no relationships between catchment characteristics and model parameters. Johansson (1994) studied relationships between parameter values and 12 catchment characteristics in 11 catchments in southern Sweden, but found a relationship only for one parameter.

2. Material and methods

2.1. The HBV model

The HBV model (Bergström, 1976) is a conceptual model of catchment hydrology which simulates daily discharge using daily rainfall and air temperature and monthly estimates of potential evaporation as input. The model consists of a snow routine representing snow accumulation and snow melt by a degree-day method, a soil routine where groundwater recharge and actual evaporation are computed as functions of actual water storage, a response routine with three linear reservoir equations and a routing routine using a triangular weighting function. Descriptions of the model can be found elsewhere (e.g., Bergström, 1992, 1995; Harlin and Kung, 1992) and in Appendix A.

The version of the model used in this study, 'HBV light' (Seibert, 1997b) corresponds to the HBV-6 version described by Bergström (1992) with only two slight changes. Instead of starting the simulation with some user-defined initial state values, the new version uses a warming-up period during which state variables evolve from standard initial values to their correct values according to meteorological conditions and parameter values. Furthermore, the restriction that only integer values are allowed for the routing parameter MAXBAS has been removed. In this study the HBV model was applied using only one land use and one elevation zone. Furthermore, to reduce the number of parameters in the response routine, the upper outflow from the upper groundwater box was excluded (i.e., the parameters UZL and K_0 were not used).

2.2. Study catchments

Eleven catchments located in the NOPEX area in central Sweden were used in this study. In this area elevation differences are small (about 100 m) and forest is the prevailing land use (Seibert, 1994) (Table 1). Three catchment characteristics were used in this study: the catchment area, the lake and forest percentages. In the studied area, the information on land use can be used as a rough surrogate for the information on distribution of different soil types. In general the areas with till soils are forested while the areas covered by clay soils are agricultural lands. Based on data from a total of 17 stations the areal, corrected precipitation for each catchment was calculated by Seibert (1994) using the Thiessen polygon method and correction factors given by Eriksson (1983). Temperature data was interpolated from four measurement stations. The monthly long-term mean potential evaporation was taken from Eriksson (1981). The simulation period was September 1981 to August 1990 preceded by a warming-up period of 8 months.

2.3. Monte Carlo calibration procedure

For model calibration a Monte Carlo procedure was used. By this any bias due to the calibration procedure could be ruled out and it was possible to allow for different almost equally good parameter sets (Seibert, 1997a). For each parameter, ranges of possible values were set based on the range of calibrated values from other model applications (Bergström, 1990; Braun and Renner, 1992). After initial runs the ranges were extended somewhat for those parameters where the best simulations were close to the minimum or maximum. For each catchment 300 000 parameter sets were generated using random numbers from a uniform distribution within the given ranges for each parameter (Table 2). The model was run for each parameter set and the values of three different objective functions (Table 3) were computed. Finally, those 1000 parameter sets, which gave the highest values of R_{eff} in one catchment, were tested in all other catchments.

Table 1
Characteristics of the catchments within the NOPEX area of the test catchments outside the NOPEX area

River	Station	Abbreviation	Area (km^2)	Forest (%)	Field or meadow (%)	Lake (%)
Catchments within the NOPEX area						
Lillån	Gränvad	GR	168	41.0	59.0	0
Örsundaån	Härnevi	HR	305	55.0	44.0	1.0
Hågaån	Lurbo	LU	124	77.7	27.0	0.3
Sävaån	Ransta	RA	198	66.1	33.0	0.9
Sävjaån	Sävja	SA	727	64.0	34.0	2.0
Sagån	Sörsätra	SO	612	61.0	37.9	1.1
Stabbybäcken	Stabby	ST	6.6	87.0	13.0	0
Stalbobäcken	Tärnsjö	TA	14	84.5	14.0	1.5
Fyrisån	Ulva Kvarn	UL	950	61.0	36.0	3.0
Vatthomaån	Vattholma 2	VA	284	71.0	24.2	4.8
Svartån	Åkesta Kvarn	ÅK	730	69.0	27.0	4.0
Test catchments outside the NOPEX area						
Svenbybäcken	Berg		37	71.4	28.6	0
Hargsån	Bergshamra		21.1	69.5	30.3	0.2
Åssingån	Fellingsbro		294	64.8	29.2	6.0
Prästhyttebäcken	Finntorpet		6.8	95.3	0	4.7
Svartån	Karlslund 2		1284	63.2	30.2	6.6
Kölstaån	Odensvibron 2		112	69	24.7	6.3
Vallsjöbäcken	Skräddartorp		19	96.2	1.3	2.5

2.4. Combination of different objective functions by a fuzzy measure

Different objective functions judge the goodness of a certain parameter set by different aspects. One parameter set can, for instance, give a good fit according to the R_{eff}-criteria but only a poor fit in terms of the V_{E} criteria and vice versa. It is difficult to combine the values of different objective functions, as they are not directly comparable. Therefore the use of fuzzy

Table 2
Model parameters and their ranges used in the Monte Carlo calibration procedure

Parameter	Explanation	Minimum	Maximum	Unit
Snow routine				
TT	Threshold temperature	−1.5	2.5	°C
CFMAX	Degree-day factor	1	10	mm °C^{-1} d^{-1}
SFCF	Snowfall correction factor	0.4	1	–
CWH	Water holding capacity	0	0.2	–
CFR	Refreezing coefficient	0	0.1	–
Soil routine				
FC	Maximum of SM (storage in soil box)	50	500	mm
LP	Threshold for reduction of evaporation (SM/FC)	0.3	1	–
BETA	Shape coefficient	1	6	–
CET	Correction factor for potential evaporation	0	0.3	°C^{-1}
Response routine				
K_1	Recession coefficient (upper box)	0.01	0.4	d^{-1}
K_2	Recession coefficient (lower box)	0.001	0.15	d^{-1}
PERC	Maximal flow from upper to lower box	0	3	mm d^{-1}
MAXBAS	Routing, length of weighting function	1	7	d

Table 3
Objective functions

Objective function	Calculation	Value of a 'perfect' fit
R_{eff}	$1-\frac{\sum(Q_{\mathrm{obs}}-Q_{\mathrm{sim}})^2}{\sum(Q_{\mathrm{obs}}-\overline{Q_{\mathrm{obs}}})^2}$	1
L_{eff}	$1-\frac{\sum(\ln Q_{\mathrm{obs}}-\ln Q_{\mathrm{sim}})^2}{\sum(\ln Q_{\mathrm{obs}}-\overline{\ln Q_{\mathrm{obs}}})^2}$	1
V_{E}	$\left\lvert\frac{\sum(Q_{\mathrm{obs}}-Q_{\mathrm{sim}})}{\sum Q_{\mathrm{obs}}}\right\rvert$	0[a]

[a] This value is necessary for a 'perfect' fit, but it does not ensure a 'perfect' fit.

measures, which allows the combination of different objective functions, has been proposed by Seibert (1997a). Membership functions were defined to transform the values of each objective function into a fuzzy measure, which evaluates the degree of truth of the statement 'this parameter set is the best possible set'. The value one was assigned to the highest values obtained for R_{eff} and L_{eff} in the respective catchment ($R_{\mathrm{eff,max}}$ and $L_{\mathrm{eff,max}}$) and a value of zero for V_{E}. The combined fuzzy measure of model goodness, F, was computed as minimum of these three fuzzy measures (Eq. (1)). This means that, for instance, a simulation with a volume error, V_{E}, of 0.1 at best could get a value of 0.5 for F.

$$F = X_1 \cap X_2 \cap X_3 = \min(X_1, X_2, X_3) \tag{1}$$

where

$$X_1(R_{\mathrm{eff}}) = \max\left(0,\ \frac{R_{\mathrm{eff}}-0.8R_{\mathrm{eff,max}}}{0.2R_{\mathrm{eff,max}}}\right),$$

$$X_2(L_{\mathrm{eff}}) = \max\left(0,\ \frac{L_{\mathrm{eff}}-0.8\ L_{\mathrm{eff,max}}}{0.2\ L_{\mathrm{eff,max}}}\right),$$

$$X_3(V_{\mathrm{E}}) = \max(0,\ 1-5\ |V_{\mathrm{E}}|)$$

2.5. Correlation between parameters and catchment characteristics

Three different assemblages of optimised parameter values from all catchments were used in the further analysis: the parameter sets which gave the best results according to the R_{eff} (A1) and the F criteria (A2) and the median values from all 'almost equally good' (as defined below) parameter sets according to the R_{eff} criteria (A3). Values for each model parameter were plotted against catchment characteristics (area, lake percentage, percentage of forested area). The aim in this first step was to evaluate the correlations rather than to derive some functional relationships and, therefore, Spearman rank correlation coefficients, r_{R}, were calculated. The non-parametric correlation was chosen for two reasons: it is a more robust measure than, for instance, linear correlation and only monotony, but no fixed shape of the functional relationship, had to be presupposed.

2.6. Estimation of regional parameters

The aim of the next step was to establish functional relationships between catchment characteristics and parameter values. This could not be achieved with the non-parametric correlation used in the first step. Instead different two-parametric regression functions (linear, exponential, power and log) were fitted to the relationships. This was done for both assemblages A1 and A2. For each parameter the function with the highest correlation coefficient, r, was chosen under the condition that r^2 was at least 0.25. Otherwise, the median parameter value from all catchments was used. The goodness of these two regional model parameter sets was assessed by applying them to two groups of catchments. At first parameter sets were compiled for the eleven catchments used to derive the equations, and runoff was simulated. Obviously, this was not a very rigorous test. It may be assumed, however, that leaving out any one of the eleven catchments from the beginning would not have changed the equations significantly. As a more severe test the regional model parameters were applied to seven catchments in the eastern and southern surroundings of the NOPEX area (Table 1). These catchments were located up to about 100 km outside the NOPEX area and, most of them, in a different kind of landscape with a higher lake percentage and larger elevation differences. The lake percentage of three catchments exceeded that of the NOPEX catchments, but no catchment had a lake percentage above 7%. In both cases the goodness of the model predictions was compared with the goodness of the simple prediction using a regional mean runoff series, where the mean specific runoff, q_{mean} (mm d^{-1}), at day t was computed as the arithmetic mean of the specific runoff from the eleven NOPEX catchments, q_i (mm d^{-1}) (Eq. (2)).

$$q_{\mathrm{mean}}(t) = \frac{1}{11}\sum_{i=1}^{11} q_i(t) \qquad (2)$$

3. Results

Good simulations with R_{eff} values between 0.79 and 0.88 could be obtained for nine catchments, while for the two smaller catchments the values were 0.70 (Stabby) and 0.73 (Tärnsjö), respectively (Table 4). The values for the fuzzy measure, F, were around 0.85. For two catchments the same parameter sets gave best results according to both the R_{eff} and F criteria, whereas sets with lower R_{eff} values were found to be best according to the F criteria in the other catchments (difference of R_{eff} between 0.01 and 0.05, mean 0.025). Based on this, the range of 'almost equally good' fits according to the R_{eff} criteria was defined to extend up to 0.02 below the highest R_{eff} value obtained for each catchment.

3.1. Correlation between the 'best' parameters and catchment characteristics

About half of the parameters were significantly ($\alpha = 0.1$) correlated to catchment characteristics (Table 5, Figs. 1 and 2). The strongest correlation was found to exist between lake percentage and K_1, with decreasing K_1 values for increasing lake percentage (Fig. 1a and Fig. 2a). The same trend was found for K_2, but the correlation was weaker. While for K_1 and K_2 relationships with significant correlation existed independent on the used assemblage of parameter, such relationships were only found in some of the three cases for the other parameters. Catchment area and the values of BETA were highly correlated when looking at the best parameter sets according to the R_{eff} criteria (Fig. 1c) but there was no significant correlation when using the best values according to the F criteria. Other significant relationships for at least one of the assemblages were found between lake

Table 4
Efficiency, R_{eff}, after calibration and for runoff simulations using regional parameter sets (Table 6) as well as regional mean runoff series

River	Station	R_{eff} (calibrated)	Goodness (R_{eff}) of runoff predicted by...		
			Regional parameter set (A1)	Regional parameter set (A2)	Regional mean runoff series
Catchments within the NOPEX area					
Lillån	Gränvad	0.81	0.80	0.79	0.72
Örsundaån	Härnevi	0.81	0.79	0.79	0.85
Hågaån	Lurbo	0.81	0.73	0.78	0.88
Sävaån	Ransta	0.82	0.79	0.79	0.94
Sävjaån	Sävja	0.86	0.86	0.86	0.81
Sagån	Sörsätra	0.79	0.71	0.71	0.78
Stabbybäcken	Stabby	0.70	0.62	0.63	0.81
Stalbobäcken	Tärnsjö	0.73	0.52	0.50	0.46
Fyrisån	Ulva Kvarn	0.81	0.55	0.68	0.60
Vatthomaån	Vattholma 2	0.86	0.82	0.79	0.33
Svartån	Åkesta Kvarn	0.88	0.79	0.78	0.62
Test catchments outside the NOPEX area					
Svenbybäcken	Berg	–	0.68	0.62	0.65
Hargsån	Bergshamra	–	0.76	0.73	0.67
Åssingån	Fellingsbro	–	0.67	0.56	0.57
Prästhyttebäcken	Finntorpet	–	0.43	0.46	0.23
Svartån	Karlslund 2	–	0.53	0.49	0.45
Kölstaån	Odensvibron 2	–	0.42	0.43	0.72
Vallsjöbäcken	Skräddartorp	–	0.70	0.67	0.62

Table 5
Correlation between catchment characteristics and parameter values[a]

Characteristic	Parameter	Parameters calibrated according to...		Median values of all good[b] parameter sets (A3)
		Efficiency (A1)	Fuzzy measure (A2)	
Lake percentage	K_1	**−0.86**	**−0.88**	**−0.91**
Lake percentage	K_2	−0.60	**−0.67**	**−0.75**
Lake percentage	FC	0.55	**0.67**	*
Lake percentage	BETA	**0.63**	*	*
Lake percentage	CET	−0.57	*	*
Forest percentage	CFMAX	*	**−0.66**	*
Forest percentage	SFCF	*	−0.54	*
Forest percentage	CFR	**0.61**	0.56	*
Forest percentage	K_2	−0.55	*	−0.54
Catchment area	BETA	**0.87**	*	0.60
Catchment area	K_1	*	−0.55	−0.55

[a] Spearman rank correlation coefficients, * denotes not significant at 0.1 level, bold denotes significant at 0.05 level.
[b] Sets that resulted in a R_{eff} value not more than 0.02 below the highest value obtained for each catchment.

percentage and FC, BETA and CET, between catchment area and K_1 and between forest percentage and CFMAX, SFCF, CFR and K_2.

Some relationships that had been expected were found only partly. The degree-day factor, CFMAX, was expected to decrease with increasing forest percentage (Troendle and King, 1985; Bergström, 1990). However, the correlation was significant only when using the best values according to the *F* criteria (A2), and r_R was only around −0.4 for the other two assemblages (Fig. 1d and Fig. 2d). The snowfall correction factor, SFCF, compensates for the fact, that evaporation of snow, which may be significant in forested areas (Troendle and King, 1985; Lundberg and Halldin, 1994), is not simulated by the model. Lower values of SFCF reduce the water equivalent of the snow pack. Therefore, SFCF was expected to decrease with increasing forest percentage. This was found in one assemblage (A2, Fig. 2c), but not in the other two cases (r_R around −0.1). MAXBAS was expected to increase with increasing catchment area and/or lake percentage, but there was no correlation to catchment area (r_R around 0.1) and the correlation to lake percentage was very weak (r_R around 0.4). The values of FC, LP and BETA could have been expected to depend on forest percentage, especially because of the relationship between land use and soil types mentioned above. However, there was virtually no correlation between the forest percentage and any of the soil-routine parameters (r_R around ±0.1–0.2).

3.2. Regional parameter sets

For about half of the parameters functional relationships to catchment characteristics were found (with $r^2 \geq 0.25$), while median values were used for the other parameters (Table 6). The largest difference in the two parameterisations was found in the response routine. Compared to A2 larger values of PERC and K_2 in A1 generally increased the significance of contributions from the lower box to runoff even during high flow conditions.

The runoff simulated using the regional parameter sets agreed well with the observed runoff for most catchments, even though the fits were not as good as for the calibrated parameter sets (Fig. 3). The two parameterisations performed equally well in terms of R_{eff} values, but the parameterisation derived from the *F* criteria parameters gave better fits during low flow conditions (median of $L_{\mathrm{eff}} = 0.73$ compared to 0.09). As a further test on the significance of the regression equations two different parameter sets were applied to all catchments: the first consisted of median values of the best parameter values (A1) for all parameters, the second corresponded to the first except the use of the regression equation for K_1. K_1 was chosen because of its high correlation to the lake percentage. The first set

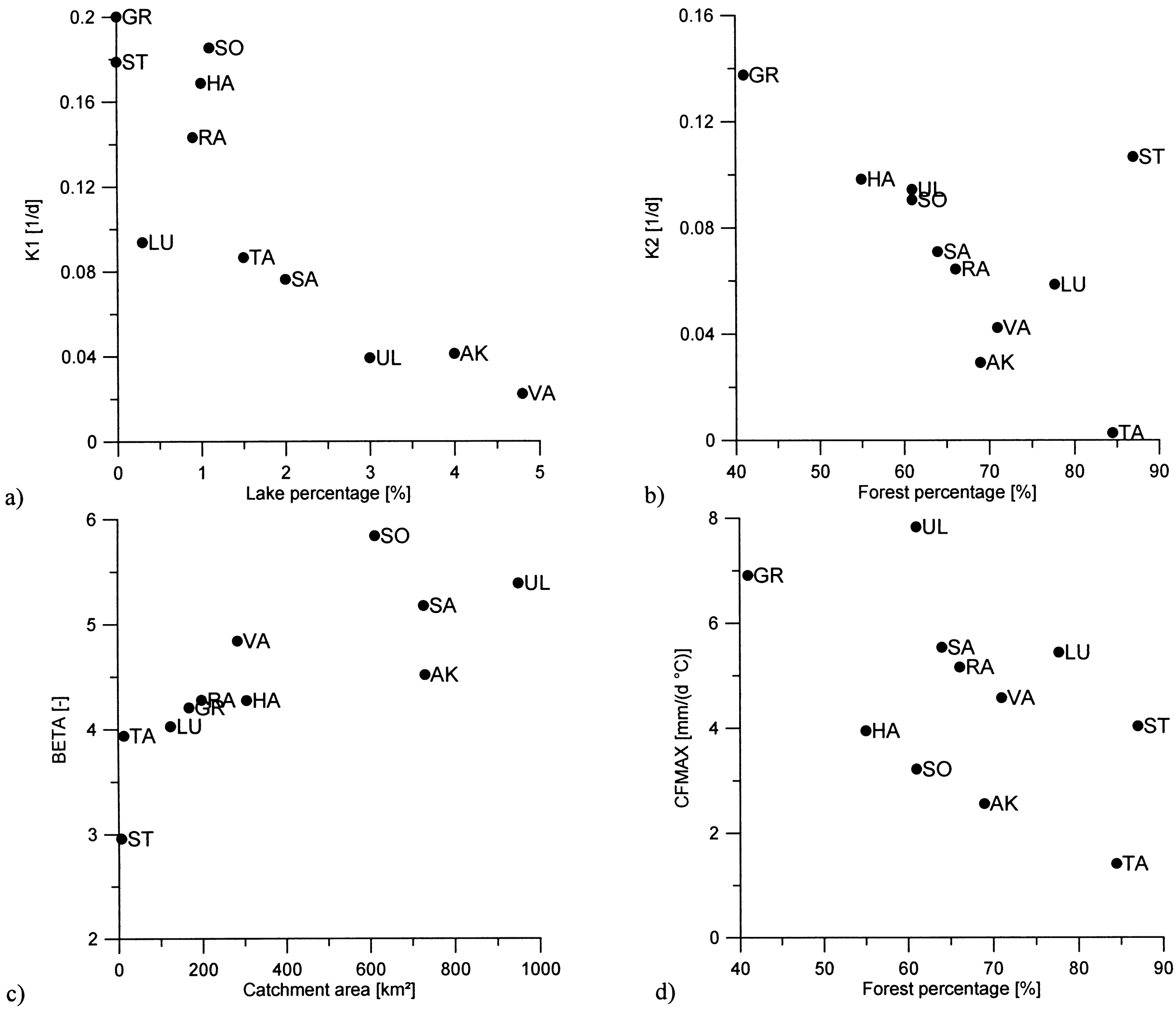
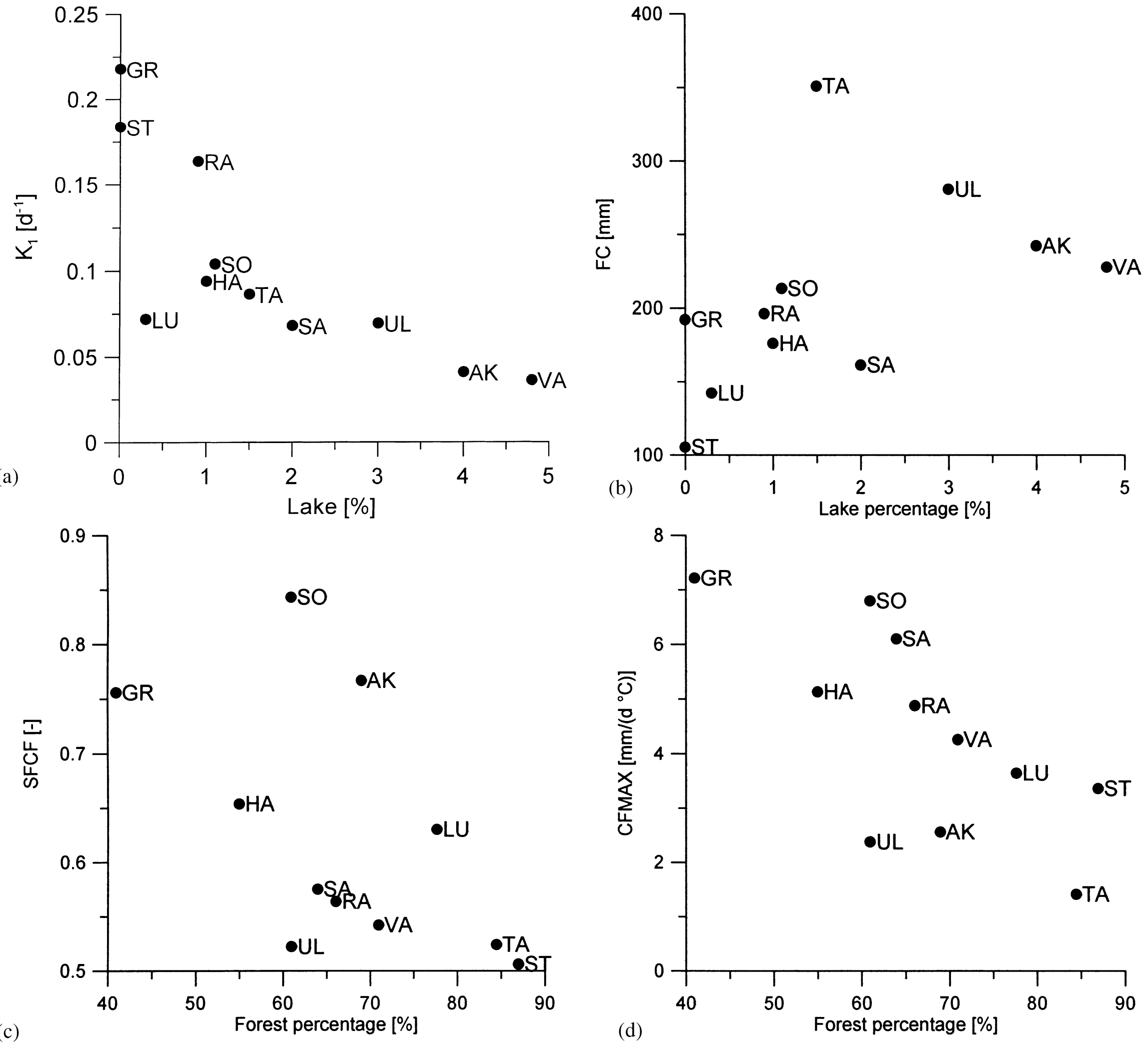


Fig. 1. Best model parameter values according to the R_{eff} criteria (A1) against catchment characteristics.

yielded less successful results, but the second gave almost as good results as using regression equations for six parameters (Table 4, Fig. 3).

The second test was to apply the regional parameter sets to independent test catchments outside the NOPEX area. As for the first test, the two parameterisations performed almost equally well, but in general the results were less satisfactory (Table 4, Fig. 3). The R_{eff} values were higher for the first parameter set (A1), whereas the predictions of the second (A2) were superior in terms of L_{eff} values (median A1: 0.15, A2: 0.56). The results for the four catchments with a lake percentage below the highest value for the NOPEX catchments (4.8%) were acceptable except for the station Finntorpet (River Prästhyttebäcken).

Using the regional mean specific runoff computed from the NOPEX catchments to predict runoff from a certain NOPEX catchment gave R_{eff} values of the same order as the regionalised model for the NOPEX catchments, whereas for the independent test catchments the R_{eff} values of the model predictions were a little higher (Fig. 3). In terms of L_{eff} values the predictions were better than that of the A2 parameter set for the NOPEX catchments (median 0.83) but of



(a) (b) (c) (d)

Fig. 2. Best model parameter values according to the *F* criteria (A2) against catchment characteristics.

the same quality for the other catchments (0.55). The mean water balance error, V_E, was about 0.1 for both groups of catchments independent of the method used for prediction.

4. Discussion

The HBV model was applied using a minimum number of parameters, i.e., only one vegetation zone, no subbasins and a reduced number of parameters in the response function. Nevertheless, parameter sets that gave an acceptable agreement between observed and simulated hydrograph ($R_{eff} > \sim 0.8$) could be found for all catchments with somewhat poorer results for the two smaller catchments Stabby and Tärnsjö. Excluding the two smaller catchments from the analysis did not alter the correlation of parameter values to catchment characteristics substantially. The only significant changes were higher correlation coefficients between forest percentage and K_2 values ($r_R = -0.93$ compared to -0.60, Fig. 1b) as well as between catchment area and the values of PERC ($r_R = 0.77$ compared to 0.40) for the assemblage

Table 6
Regional parameter values for the NOPEX area derived from the best parameter sets according to the efficiency, R_{eff}, and the fuzzy measure, F[a]

Parameter (units: see Table 2)	Efficiency (A1)		Fuzzy-measure (A2)	
	Function/value	Correlation coefficient, r	Function/value	Correlation coefficient, r
TT	1.1	–	1.1	–
CFMAX	$-0.074C_{FOREST}+9.6$	−0.53	$-0.101C_{FOREST}+11.1$	−0.71
SFCF	0.61	–	$-0.005C_{FOREST}+0.95$	−0.55
CWH	0.06	–	$0.0013C_{FOREST}-0.044$	0.60
CFR	0.05	–	0.07	–
FC	205	–	$165\exp(0.11C_{LAKE})$	0.55
LP	0.66	–	0.57	–
BETA	$2.63A^{0.099}$	0.87	4.0	–
CET	$-0.02C_{LAKE}+0.16$	−0.50	0.10	–
K_1	$0.19\exp(-0.43C_{LAKE})$	−0.93	$0.15\exp(-0.31C_{LAKE})$	−0.87
K_2	$-0.0018C_{FOREST}+0.192$	−0.62	$-0.006C_{LAKE}+0.044$	−0.61
PERC	1.80	–	0.64	–
MAXBAS	$0.5C_{LAKE}+2.0$	0.50	2.2	–

[a] Forest percentage, C_{FOREST} (%), lake percentage, C_{LAKE} (%) and area, A (km^2), the equations may not be valid outside the following limits: C_{FOREST} 40–90%, C_{LAKE} 0–5% and A 6–1000 km^2.

A1. Two of the catchments (Åkesta kvarn and Ransta) are used as so-called 'indicator catchments' by SMHI (Swedish Meteorological and Hydrological Institute) where the HBV model is used for runoff forecasting (Lidén, 1995). Although more parameters are used in the SMHI-application, the model goodness in terms of R_{eff} values (0.88 (1981–1990, ÅK) and 0.84 (1982–1992, RA)) is hardly better than that obtained in this study. Therefore, it was concluded that using a minimum number of parameters probably did not lower the R_{eff} values significantly.

The lake percentage was found to be correlated with several parameters. While the relationships with the recession parameters K_1 and K_2 were expected, the

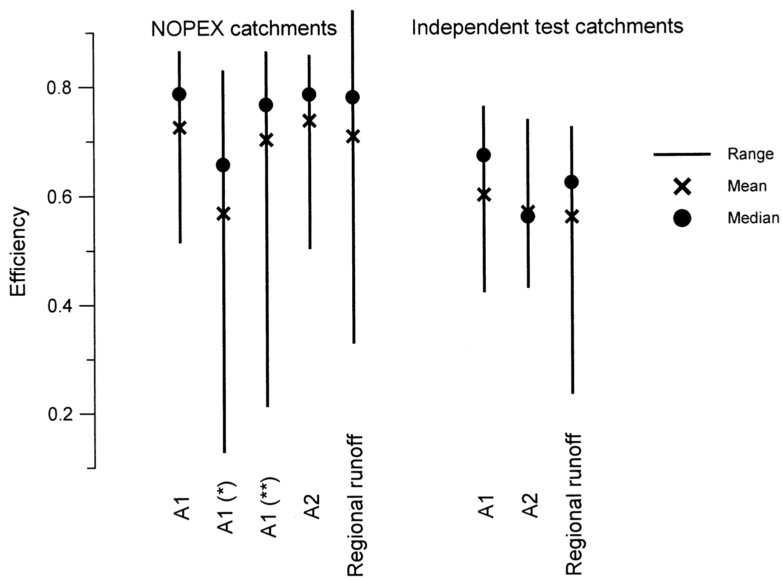


Fig. 3. Goodness of runoff series prediction by regional parameters sets and the regional mean runoff series.

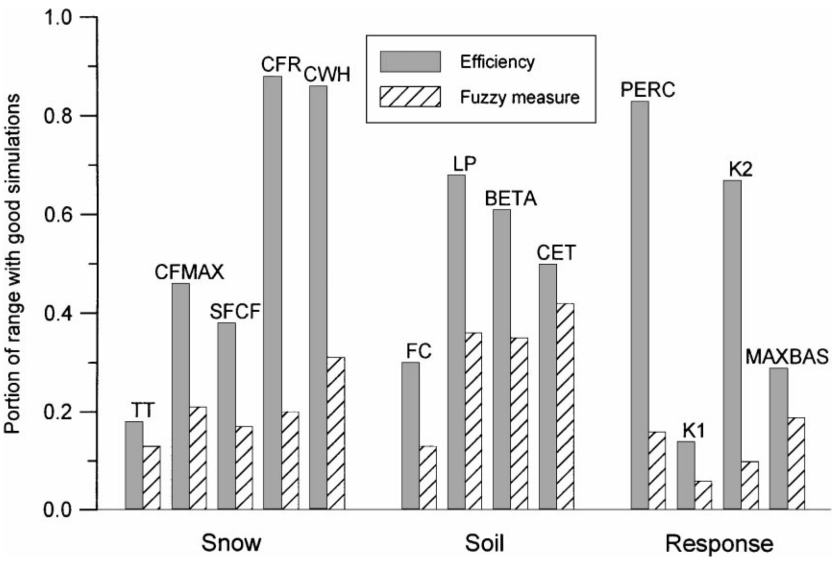


Fig. 4. Range of 'good' parameter values. For each parameter the range over which 'good fits' could be obtained is given as a portion of its entire tested range (Table 2) (median values from all 11 catchments within the NOPEX area, 'good fits' were defined as fits with R_{eff} not more than 0.02 and F not more than 0.1 less than the highest values obtained for each catchment respectively).

relationships with FC, BETA and CET need to be discussed. There is hardly any physical explanation why a larger lake percentage should cause, for instance, a larger water storage capacity of the soils. However, both lower values of CET and larger values of FC and BETA give rise to a more damped and even hydrograph, i.e., the effect of lakes for runoff routing is to some degree incorporated into those parts of the model which actually represents the processes in the soil. As a result relationships between these parameters and the forest percentage might have been hidden, i.e., from the discharge stations the soils and forests behind the lakes could not be seen by the model. The high correlation between area and BETA may be explained in a similar way as discussed above for the lake percentage. However, BETA can be interpreted as an indicator of the relationship between the catchment soil moisture and the extension of contributing areas. Therefore, an alternative explanation of the correlation is that the relative contributing area tends to be larger in small catchments than in larger ones.

There are two reasons for the lack of a significant correlation between MAXBAS and lake percentage or catchment area. The variations K_1 and MAXBAS had similar effects on the simulated hydrograph, i.e., as K_1 varied with lake percentage the necessity of MAXBAS to vary diminished. Furthermore, the differences in catchment area were relatively small taking the daily time step into account.

A dependence of the snow parameters CFMAX and SFCF on forest percentage had been expected from experimental studies (e.g., Troendle and King, 1985; Lundberg and Halldin, 1994). The fact that the negative correlation was significant at least when using the assemblage A2 consequently provides support for the physical basis of the snow routine. On the other hand, at present the representation of losses from the snow pack due to evaporation of intercepted snow by a correction factor for snowfall is rather coarse. The increase of values for the refreezing coefficient CFR with increasing forest percentage can be explained as a compensation for the opposite trend of CFMAX, because the degree-day factor for refreezing is computed as product of CFR and CFMAX.

Many model parameters were badly defined, i.e., good fits according to the R_{eff} criteria could be obtained over a large range of values (Fig. 4). This parameter uncertainty has to be considered when interpreting the relationships between model parameters and catchment characteristics. More or less accidental variations of parameter values may have

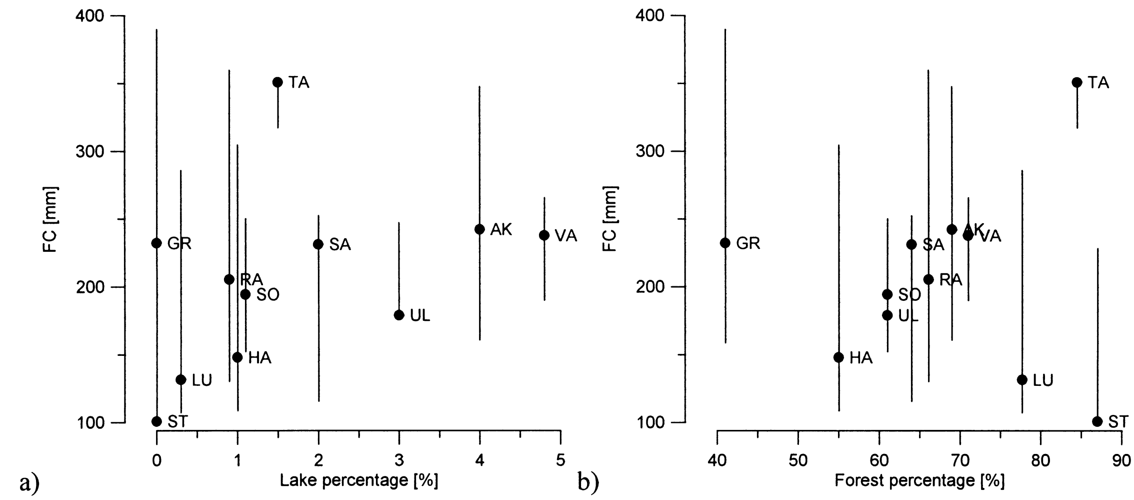


Fig. 5. Values for FC according to the R_{eff} criteria (A1) against forest percentage, both best model parameter values (●) and ranges over which 'good fits' (i.e., R_{eff} not more than 0.02 less than the highest values obtain for each catchment, respectively) could be obtained are shown.

prevented the detection of relationships, but may also have generated relationships (Fig. 5). As a more robust assemblage median values of all good parameter sets instead of only the one best parameter set for each catchment were tested. The results agreed in general, but the relationships between lake percentage and soil parameters became weaker. Using the fuzzy measure allows to rate parameter sets based on the goodness of two other objective functions in addition to the efficiency. The parameter uncertainty was reduced (Fig. 4) and, therefore, the confidence in the relationships derived from the fuzzy measure assemblage increased.

Another complication in the interpretation of relationships between catchment characteristics and model parameters is that catchment characteristics might be intercorrelated. For the catchments in the NOPEX area, the lake percentage tend to increase with catchment area ($r_{\mathrm{R}} = 0.68$) and forest percentage to decrease with catchment area ($r_{\mathrm{R}} = -0.55$), while there is no correlation between lake and forest percentage ($r_{\mathrm{R}} = 0.03$). Therefore, the relationship between, for instance, lake percentage and FC could also be interpreted as relationship between catchment area and FC, which might be more sensible physically.

The results of this study have to be interpreted with care as only eleven catchments were used. On the other hand, using only a limited number of catchments allowed to use catchments that were all located in a geographically fairly homogenous region. Mean annual precipitation, for instance, did not vary with more than 10% among the catchments. In some other studies precipitation varied considerably and model parameters were found to be correlated to precipitation (e.g., Servat and Dezetter, 1993; Ibrahim and Cordery, 1995). Multiple relationships (e.g., Magette et al., 1976; Hughes, 1989) or derived characteristics (Ross, 1970) were needed in many other studies. The relatively small study area was assumed to be the reason that at least some of the variation of parameter values could be explained by single catchment characteristics. Obviously, the restriction to a small area has the disadvantage that the applicability of the derived regional parameter sets also is limited in space.

The regional parameter sets performed well for the NOPEX catchments, but the results where poorer for the independent test catchments. One explanation for this was, of course, that the parameter sets were derived from the NOPEX catchments. However, for the four independent catchments with a lake percentage that did not exceed that of the NOPEX catchments results were acceptable except for one catchment. This indicated that the decrease of model goodness for the regional parameter sets outside the NOPEX catchments at least partly could be attributed to the application of the regression equations beyond the range from which they were derived.

The regional mean specific runoff series performed almost equally well as the regionalised model. This indicates that such a simple way to calculate series may be sufficient when only runoff series and not a model is needed for a ungauged catchment. It should be noted that using runoff series from only one catchment instead of an average would include the risk of very bad predictions. Seibert (1994) calculated the goodness of predicting specific runoff series for a certain catchment by one other catchment for all pairs of NOPEX catchments. The median R_{eff} value was 0.66, the range was much larger than that obtained using the regional mean runoff series and the minimum value was -0.59.

5. Concluding remarks

Several relationships between model parameters and catchment characteristics could be found. Some relationships between lake percentage and soil parameters called the physical basis of the model into question as they could not be explained by the physical processes in the soil but by the dominating effect of lakes to runoff variations. On the other hand, relationships between forest percentage and snow parameters supported the physical basis of the model as they had been expected from results of experimental studies found in literature.

The large influence of the lake percentage on the runoff dynamics may mask other relationships between parameter values and catchment characteristics. Furthermore, the dependence of the parameters representing the hydrological processes on lake percentage calls the physical basis of the model into question. Therefore, it may be reasonable to simulate lakes more explicitly than what is done by the recession and routing parameters, e.g., dividing the catchment in parts up and downstream of lakes. However, in the boreal landscape with its small but numerous lakes this approach is not straightforward, because such a division would result in many subbasins with the need of new parameters for the simulation of outflow from the different lakes.

Parameter uncertainty due to interrelations between model parameters complicates the regionalisation of model parameters because optimised parameter values may vary by chance between a range of values. Therefore, ways to reduce this uncertainty are of importance for the regionalisation of model parameters. In this study, a fuzzy measure, which allowed to combine different objective functions, was used to determine optimised parameter sets. Another method to reduce parameter uncertainty is to include additional data beyond observed runoff into the calibration procedure (e.g., de Grosbois et al., 1988; Franks et al., 1998).

Even though the goodness of the simulations using regional parameter sets in general was acceptable, the comparison with the simple method of using the mean of runoff series from neighbouring catchments called the approach to use conceptual rainfall-runoff models for runoff prediction at ungauged catchments into question. In similar studies results are usually not compared to those using other methods. From the results of this study further research can be recommended to weigh pros and cons of the model approach compared to other methods (e.g., Hirsch, 1979, 1982). However, even if relationships between catchment characteristics and model parameters will not lead to the best predictions of runoff at ungauged stations, studies of these relationships still are of value as a means to discuss and improve the physical basis of conceptual models.

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Appendix A. A short description of the HBV model

The model simulates daily discharge using daily rainfall, temperature and potential evaporation as input. Precipitation is simulated to be either snow or rain depending on whether the temperature is above or below a threshold temperature, TT (°C). All precipitation simulated to be snow, i.e., falling when the temperature is below TT, is multiplied by a snowfall correction factor, SFCF, which represents systematic errors in the snowfall measurements and the 'missing' evaporation from the snow pack in the model. Snowmelt is calculated with the degree-day method (Eq. (A.1)). Meltwater and rainfall is retained within the snow pack until it exceeds a certain fraction, CWH, of the water equivalent of the snow. Liquid water within the snow pack refreezes according to a refreezing coefficient, CFR (Eq. (A.2)).

$$\mathrm{melt} = \mathrm{CFMAX}(T(t)-\mathrm{TT}) \tag{A.1}$$

$$\mathrm{refreezing} = \mathrm{CFR} \times \mathrm{CFMAX}\,(\mathrm{TT}-T(t)) \tag{A.2}$$

Rainfall and snow melt (P) are divided into water filling the soil box and groundwater recharge depending on the relationship between water content of the soil box (SM (mm)) and its largest value (FC (mm)) (Eq. (A.3)). Actual evaporation from the soil box equals the potential evaporation if SM/FC is above LP, while a linear reduction is used when SM/FC is below LP (Eq. (A.4)).

$$\frac{\mathrm{recharge}}{P(t)} = \left(\frac{\mathrm{SM}(t)}{\mathrm{FC}}\right)^{\mathrm{BETA}} \tag{A.3}$$

$$E_{\mathrm{act}} = E_{\mathrm{pot}} \min\left(\frac{\mathrm{SM}(t)}{\mathrm{FC} \times \mathrm{LP}},\ 1\right) \tag{A.4}$$

Groundwater recharge is added to the upper groundwater box (SUZ (mm)). PERC (mm d^{-1}) defines the maximum percolation rate from the upper to the lower groundwater box (SLZ (mm)). For the lakes, precipitation and evaporation is added and subtracted directly from the lower box. Runoff from the groundwater boxes is computed as the sum of two or three linear outflow equations (K_0, K_1 and K_2 (d^{-1}) depending on whether SUZ is above a threshold value, UZL (mm), or not (Eq. (A.5)). This runoff is finally transformed by a triangular weighting function defined by the parameter MAXBAS (Eq. (A.6)) to give the simulated runoff (mm d^{-1}).

$$Q_{\mathrm{GW}}(t) = K_2\,\mathrm{SLZ} + K_1\,\mathrm{SUZ} + K_0 \max(\mathrm{SUZ}-\mathrm{UZL}, 0) \tag{A.5}$$

$$Q_{\sim}(t) = \sum_{i=1}^{\mathrm{MAXBAS}} c(i) Q_{\mathrm{GW}}(t-i+1) \quad \text{where}$$

$$c(i) = \int_{i-1}^{i} \frac{2}{\mathrm{MAXBAS}} - \left| u - \frac{\mathrm{MAXBAS}}{2} \right| \frac{4}{\mathrm{MAXBAS}^2}\, \mathrm{d}u$$

The long-term mean values of the potential evaporation, $E_{\mathrm{pot,M}}$, for a certain day of the year are corrected to its value at day t , $E_{\mathrm{pot}}(t)$, by using the deviations of the temperature, $T(t)$ at a certain day, from its long-term mean, T_{M}, and a correction factor, C_{ET} (°C^{-1}) (Eq. (A.7)).

$$E_{\mathrm{pot}}(t) = (1 + C_{\mathrm{ET}}(T(t)-T_{\mathrm{M}}))E_{\mathrm{pot,M}} \quad \text{but} \quad 0 \le E_{\mathrm{pot}}(t) \le 2E_{\mathrm{pot,M}} \tag{A.7}$$

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