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Application of the ETH Snow Model to Three Basins of Different Character in Central Europe

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The performance of a version of the HBV-ETH model is evaluated, taking into account various aspect classes in each elevation belt in three different types of catchments: an alpine basin, and two basins in Bohemia at much lower elevation, with a snowpack which is smaller and of shorter duration. In all three cases a reasonably good agreement between modelled and observed runoff and between modelled and observed snowpack was achieved. In the smaller of the Bohemian basins (1.87 km^2, 775-885 m a.s.l., influenced by deforestation), the effect of the presence and age or absence of forest on the development of the snow-water equivalent was found to be as important as the effect of aspect and altitude.

Introduction

The present contribution compares the performance of the HBV-ETH model (version 4) in three different types of catchments: the original alpine basin for which it was developed (Fig. 1), and two basins in Bohemia (Fig. 2) at much lower altitudes with a snowpack which is smaller and of shorter duration.

This model allows the assessment of all important terms of the water balance, however, only the performance of the simulation of snowcover and runoff is discussed here.

A large difference in the calibration procedure consists in the fact that in the

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Thur catchment the measured snow-water equivalents were used together with discharge (Hottelet *et al.* 1993). This was necessary because there were unknown karst-related losses of discharge. On the Bohemian catchments the standard method of calibration was employed, *i.e.*, fitting on the basis of discharge, and the snow-water equivalents were not in any way used for calibration. Therefore the comparison of modelled and measured snowpack is a good check of this important state variable for both the calibration and simulation period.

In one of the Bohemian catchments drastic changes in forest cover have occurred during the observation period. These were caused by deforestation and the dying of forests. The effects of vegetation changes on streamflow were assessed by Křeček and Zelený C. (1980) and Miţă (1980) in a similar setting in Central Europe. In a more recent study Brandt *et al.* (1988) investigated the effect of clearcutting with a similar model, and their results are discussed in the light of the experience reported here.

Description of the ETH Snow Model

The HBV-ETH conceptual runoff model (version 4) as presented here is based on the HBV model (Bergström 1976), meanwhile applied in more than 30 countries (Bergström 1992); it was developed by Jensen (1983) and coupled with a more detailed snow- and glaciermelt subroutine employing a seasonally-varied temperature-index approach (Braun and Lang 1986; Braun and Aellen 1990). For the study of snow-water equivalents on the north-facing slopes of the Thur catchment, version 4 was developed by Hottelet (1991) and Hottelet *et al.* (1993) which made it possible to take into account various aspect classes in each elevation belt. The degree-day factor for calculating snowmelt is described by a sinusoidal function varying between CMIN (on December 21) and CMAX (on June 21). The resulting values, which are applied in the aspect class east-west-horizontal, were multiplied by the parameter REXP (values larger than 1.0) for southern slopes and divided by the same value of REXP for northern slopes. Daily values of air temperature and precipitation served as input variables, and discharge is used for calibration and verification.

Table 1 – Optimized ETH snow model parameters for the three basins studied

Catchment	RCF	SCF	CMIN	CMAX	T0	REXP	CWH	CRFR
Thur	1.40	1.50	2.5	4.4	-0.6	1.5	0.01	0.10
Teplá	1.09	1.44	3.0	5.2	1.0	1.5	0.16	0.01
Uhlířská	1.15	1.25	2.6	2.9	-0.8	1.5	0.04	0.02

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The optimized values of the snow routine parameters for all three catchments, *i.e.*, rain correction factor (RCF), snow correction facator (SCF), minimum and maximum values of the degree-day factor (CMIN, CMAX, respectively), snow-rain transition temperature (T0), the parameter controlling the aspect-dependent melt function (REXP), water-holding capacity (CWH) and refreezing coefficient (CRFR), are given in Table 1.

Description of the Basins and Data Used

The Thur Catchment

The 96 km^2 alpine head watershed of the Thur River is situated in northeastern Switzerland (Fig. 1). In the upper regions reaching up to 2,500 m a.s.l. (Säntis peak), about 60 % of annual precipitation falls as snow. As limestone is predominant, widespread karst-hydrological features such as dolines and caverns cause large water gains and losses. Detailed investigations using dye tracer experiments allowed the delineation of a subterranean watershed with an area of 12 km^2 feeding the upper Thur basin (Leibundgut and Attinger 1988), and karst-hydrological connections between various points of the watershed and the Rinquelle lying outside the watershed (Rieg and Leibundgut 1992). Latest field experiments also revealed sub-lacustric water losses into Walensee situated south of the Thur basin (Mühlestein, Rieg and Scherrer 1992).

In order to assess the karst-related losses, two additional model parameters k3 and k4 were introduced (Hottelet *et al.* 1993). Fast-response karst losses are described by k3, which was externally derived by simulated and measured discharge from the Rinquelle, assuming that all fast-response karst losses pass through this spring. The sub-lacustric water losses into Walensee, which react rather slowly to rain and snowmelt inputs, are taken into account via k4. While no quantitative measurements of this kind of karst losses are available, it was assumed that the measured values of snowpack storage at Schwägalp (Fig. 1) reflect "true" water input due to snowfall, and the snowfall correction factor SCF was externally derived in such a way as to yield acceptable snowpack simulations at an elevation of 1,300 m a.s.l. in north-facing slopes for the calibration period 1975/76 to 1979/80. After that, the parameter k4 was set to the value 0.013 which causes a minimal difference between measured and simulated discharge (Thur) over the total calibration period, and acceptable results of both snowpack and discharge resulted. For more details on the calibration procedures see Hottelet *et al.* (1993).

The Teplá Catchment

Fig. 2 shows the topography of the Teplá catchment (286 km^2) together with the measuring stations of the Czech Hydrometeorological Institute (CHMI) and of the Ohře River Board (Kučera 1983). Two isolines of average annual precipitation are

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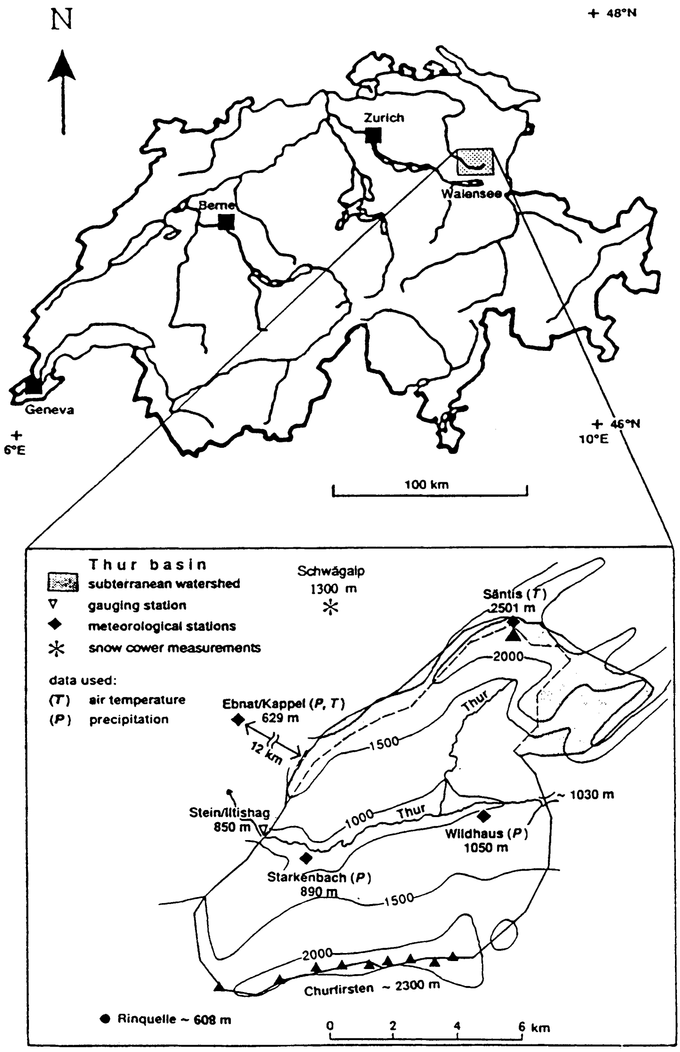

Fig. 1. Location map of the upper Thur basin, Switzerland.

also shown. The catchment lies on the lee-side of the Krušné hory and Slavkovský les mountains. In this area large storms are less frequent, and the rainfall intensities in the summer period are lower than in other areas. As a result, the annual flow maxima are caused mostly by snowmelt with rainfall. The average number of days with snow cover is 60 to 80. Average maximum snow depth in the middle and upper part of the catchment amounts to 30 or 40 cm, in the lower part to 20 or 30 cm (Vaverková 1979; Barbořík and Chamas 1970; Kreníková 1987).

The model was calibrated using data of the winter season 1986/87 (13 December

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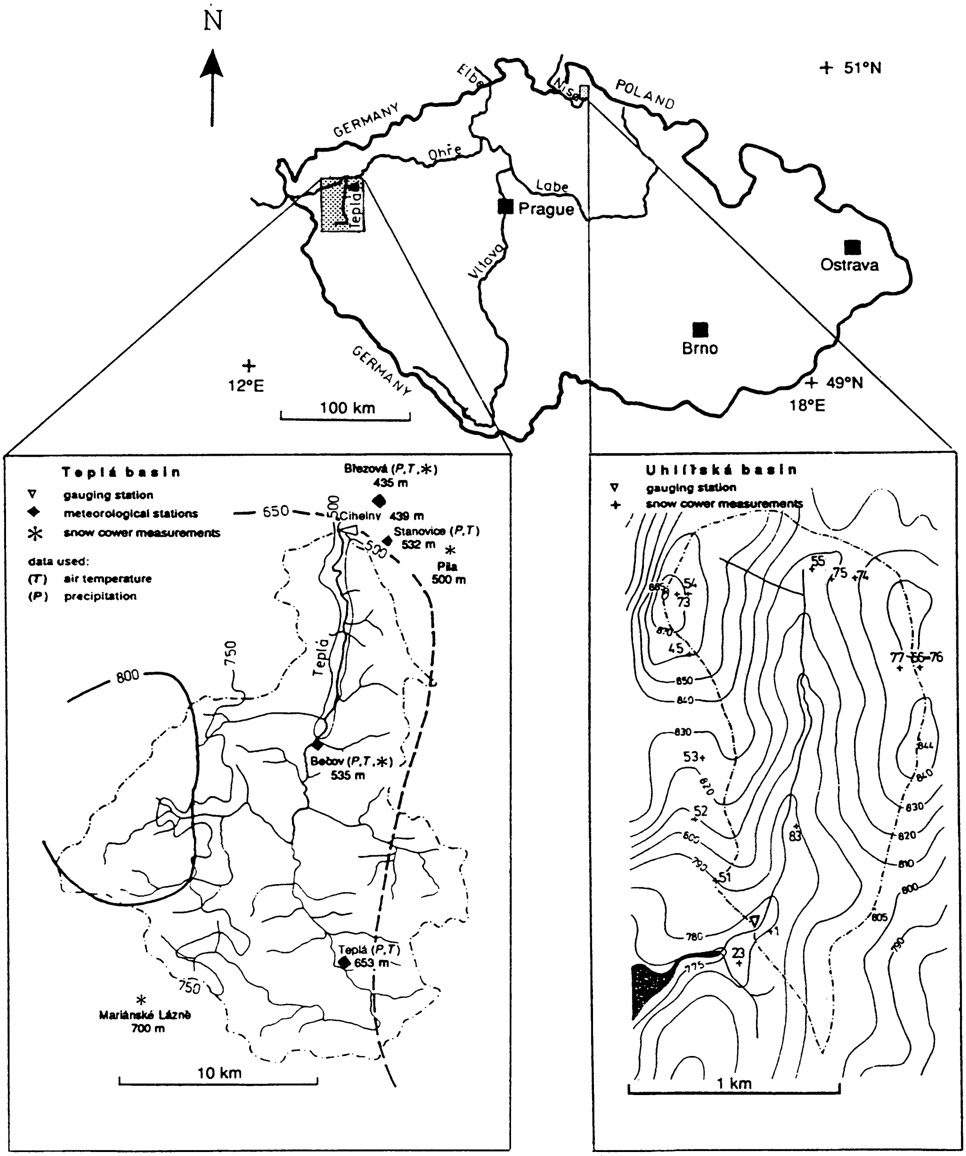

Fig. 2. Location map of the Teplá basin (with isolines of mean annual precipitation) and the Uhlířská basin on Nisa (with snow measurement sites) in Bohemia, Czech Republic.

to 2 May) which experienced an above-average snow cover. For the calibration, daily data of discharge at Cihelny and the areal average of daily precipitation at the stations Teplá, Bečov, Březová and Stanovice were used. Two temperature sta-

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tions were employed: the Teplá station corrected by subtracting 2°C in order to represent the upper part of the catchment (a value calibrated in a previous snow-modelling study), and for the lower part the arithmetic mean for Bečov, Březová and Stanovice.

The catchment has been subdivided into four elevation belts. The percentages of the expositions of slopes have been estimated from maps.

As the data period is short and does not contain a summer period, the parameters of soil moisture routine had to be set *a priori* based on the experience from other basins, and are not further discussed.

At the stations Mariánské Lázně (700 m a.s.l., south-west aspect), Bečov (535 m, north), Březová (435 m, north-west) and Pila (500 m, north) weekly snow-water equivalents have been available to assess the performance of the simulation of the snow storage.

The Uhlířská Catchment

The Jizera Mountains (Fig. 2) are severely affected by atmospheric deposition of SO_2 and heavy metals, and as a consequence, by the dying of forests. The Uhlířská catchment (1.87 km^2) on the Cerna Nisa is one of the experimental catchments of CHMI established with the aim to observe changes in hydrologic regime due to air pollution and timber harvesting (Bubeníčková *et al.* 1985).,

The Jizera Mountains are one of the coldest areas in Bohemia with extreme precipitation totals and intensities. The average annual precipitation for the period 1901 to 1950 was 1,373 mm. Snow accumulation is usually observed during December, January and February with possible melting in between. The absolute maxima of snow depth measured at the station Nová Luka (near the Uhlířská catchment, 780 m a.s.l.) for the period 1901 to 1950 were 181 cm in January, 180 cm in February, and 175 cm in March. The values of snow-water equivalent decline usually from the second half of March. Snow cover in clearings melts away in the first third of April, while in the forest the snow cover may last until May.

The Uhlířská catchment was originally forested. Since the early 1960s air pollution has damaged the forests heavily. At the beginning of 1985, 63 % of the catchment was still forested. By now the forest has been almost cleared away. Regrowth has, however, set in immediately.

For this catchment, nine years of precipitation and runoff observation on a daily time step are available (1981/82 to 1989/90). Precipitation is measured at the climatic station Bedřichov (outside the catchment) at 777 m a.s.l. Precipitation was corrected using data from a number of recording rain gauges which have been put on the mountain ridges in summer.

In winter snow measurements have been carried out. Snow sites were moved several times (Fig. 2). Site No. 1 located at the basin outlet was the one with the most frequent measurements in all eight years except 1989/90 (when there was almost no snow). Most stations are paired, *i.e.*, measurements were done both in

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the forest and in clearings. Sites differ in altitude and aspect. Snow courses at each site were about 30 m long. The mean snow-water equivalent was derived based on snow depth measurements at 10 points, and snow-water equivalent at 3 points of each course.

In the absence of more detailed information on the development of forest cover in the catchment it was decided to divide the period of measurement into two parts (see Table 2). In the first four years, both dryer and wetter summer seasons than the long-term average have occurred. The snow cover was in the first two years above average, and in the second two below average.

Table 2 – Nash and Sutcliffe efficiency criterion R^2 for the simulation of daily discharge as achieved for the various basins

			CALIBRATION PERIOD		
Thur	**1975/76**	**1976/77**	**1977/78**	**1978/79**	**1979/80**
R^2	**0.78**	**0.75**	**0.62**	**0.74**	**0.78**
Teplá	**1986/87**				
R^2	**0.90**				
Uhlířská	**1981/82**	**1982/83**	**1983/84**	**1984/85**	
R^2	**0.83**	**0.83**	**0.72**	**0.80**	
			VERIFICATION PERIOD		
Thur	**1980/81**	**1981/82**	**1982/83**	**1983/84**	**1989/90**
R^2	**0.77**	**0.68**	**0.67**	**0.68**	**0.66**
Uhlířská	**1985/86**	**1986/87**	**1987/88**	**1988/89**	**1989/90**
R^2	**0.66**	**0.73**	**0.73**	**0.29**	**0.70**

Results

The Thur Catchment

As an example, various simulations for the year 1979/80 are shown (Fig. 3). That year experienced the second highest precipitation and discharge values for the ten years investigated (verification period: 1980/81 to 1983/84 and 1989/90), and snow storage on northern slopes amounted to about 500 mm in March and April at 1,300 m a.s.l., which was about average. Simulated and measured snow-water equivalent at elevation 1,300 m and northern aspect corresponds very well, as this was one of the criteria that needed to be fulfilled when calibrating the snowfall correction factor SCF. But also during the verification period simulated snow storage corres-

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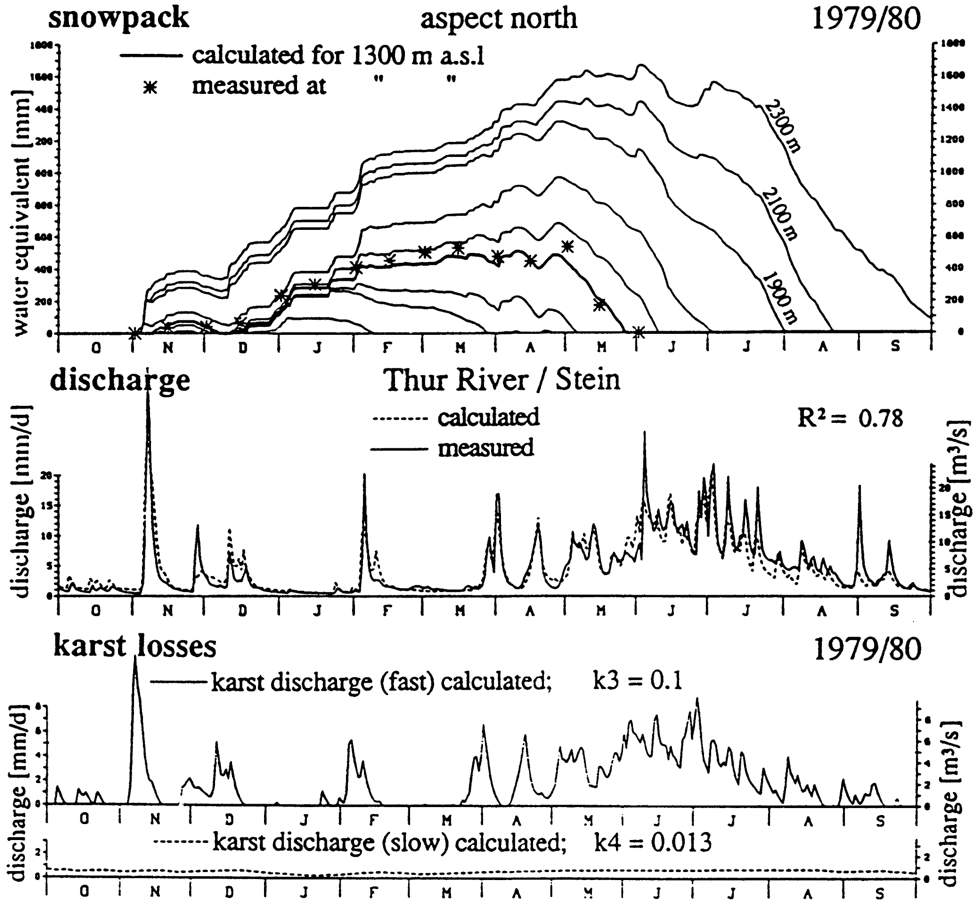

Fig. 3. Snow-water equivalent, discharge and karst losses of the upper Thur basin for the year 1979/80 (calibration period).

ponds well with measured values (Hottelet *et al.* 1993). The Nash and Sutcliffe efficiency criterion R^2 of the discharge simulation varied in the calibration period between 0.62 and 0.78, in the verification period between 0.66 and 0.77 (see Table 2). With respect to the simulated fast karst losses (outflow of the Rinquelle), one can see that the karst spring runs dry over several and extended periods of time which is supported by observation. Slow karst discharge, on the other hand, takes on rather constant values between about 0.2 and 1 m^3/s.

The Teplá Catchment

Optimal values of the snow model parameters are summarized in Table 1, and the modelled and measured discharges for winter 1986/87 are given in Fig. 4. The Nash

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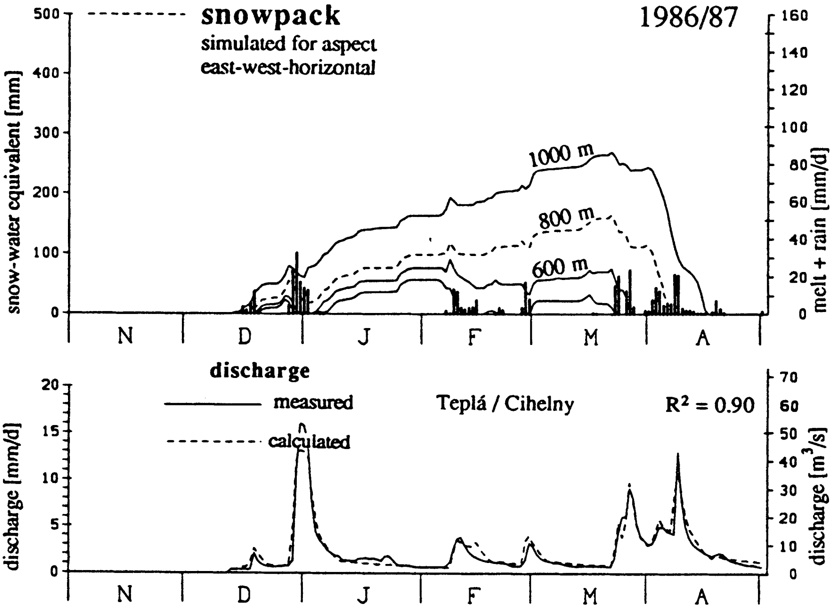

Fig. 4. Calculated snow-water equivalent, daily melt + rain input and discharge (measured and simulated) of the Teplá basin for the winter season 1986/87 (calibration period).

and Sutcliffe efficiency criterion R^2 amounts to 0.90. As model parameters were calibrated solely on the basis of discharge, measured snow-water equivalents can serve as a validation of the snow model, which can be considered satisfactory at all four locations for this winter (Fig. 5).

The Uhlířská Catchment

The R^2 criterion values in the calibration period (1981/82 to 1984/85) range between 0.72 and 0.83 (see Table 2). The peaks are modelled very well both in respect to magnitude and timing. The results of the winter season 1981/82 are shown in Fig. 6 as an example.

In the verification runs (1985/86 to 1989/90) the R^2 values dropped to values between 0.29 and 0.73. The most pronounced differences were found in the winter seasons 1986/87 and 1988/89 (Fig. 6). In these years, several discharge peaks were poorly simulated, and discharge during the main melt season was generally underestimated, but strong overestimation occurred towards the end of the ablation season.

The accumulated difference (calculated minus recorded runoff), which is well-balanced in the calibration period, becomes clearly negative in the verification period. Then, the average of the annual sum of recorded runoff is about 50 mm higher than the calculated.

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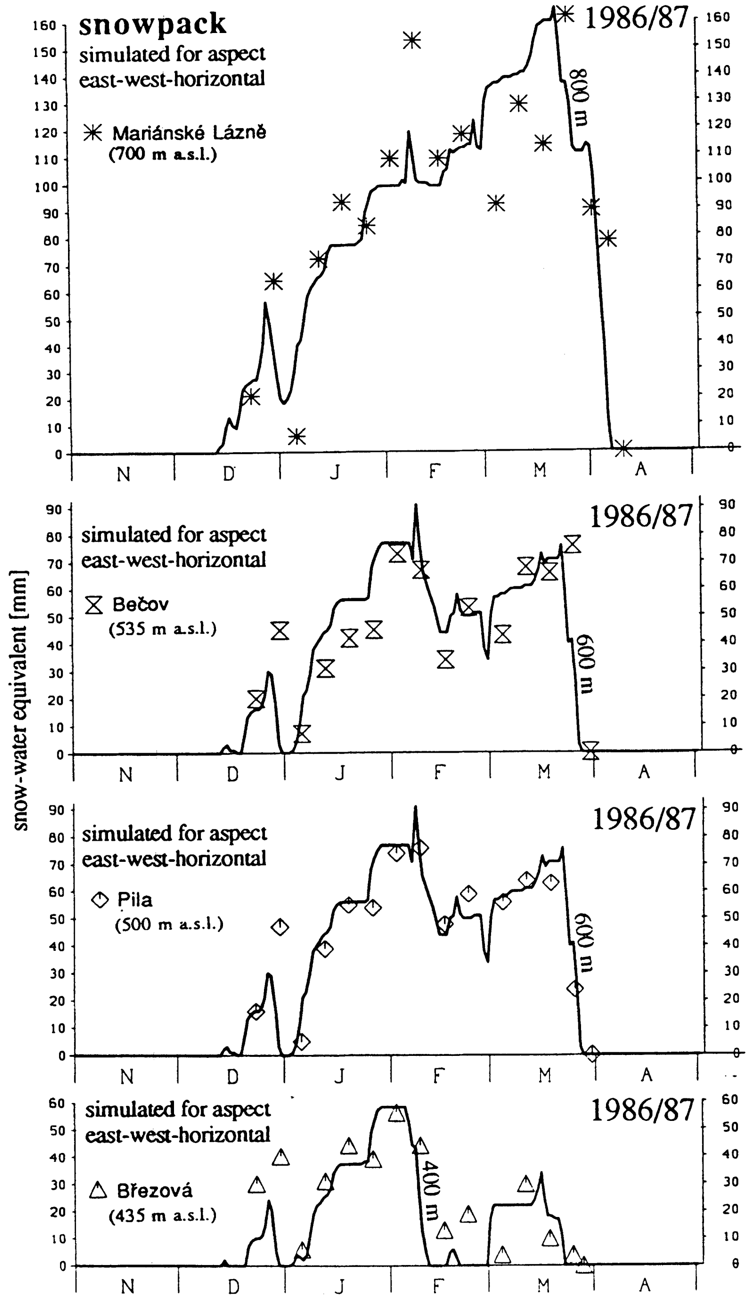

Fig. 5. Calculated snow-water equivalent at various elevations for aspect E, W, horizontal in the Teplá basin for the winter season 1986/87 and comparison with measured values.

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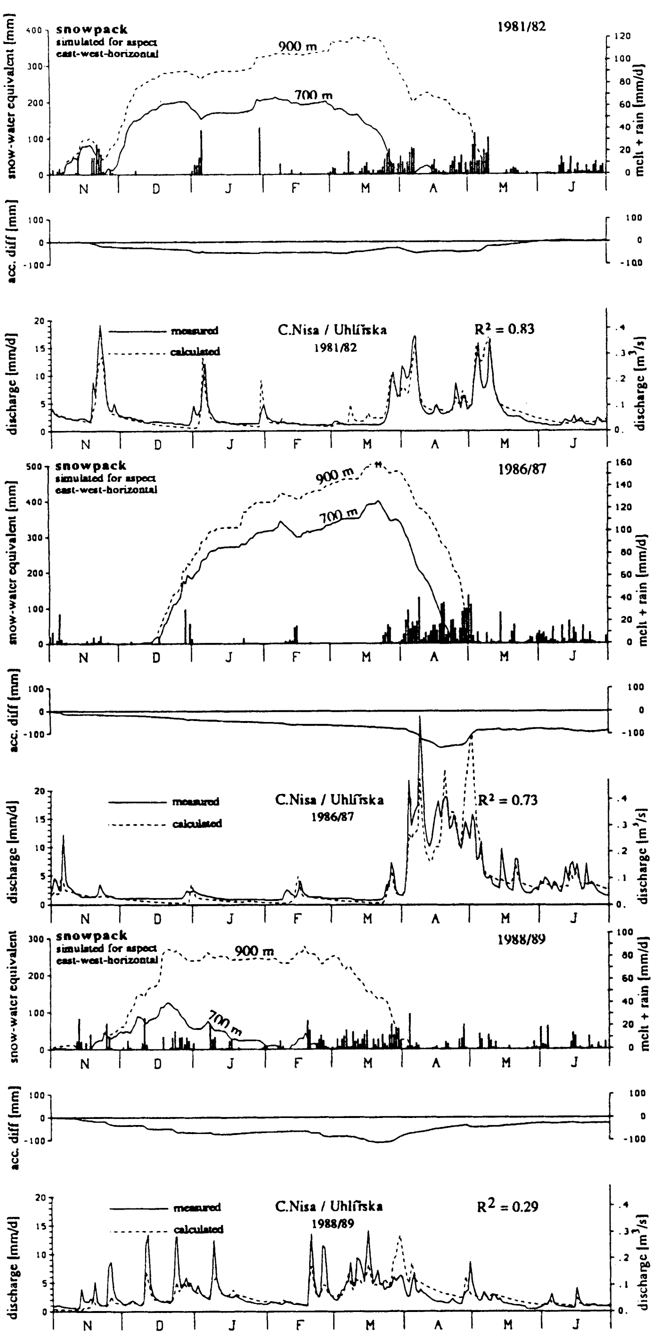

Fig. 6. Calculated snow-water equivalent, daily melt + rain input and discharge of the Uhlířská basin for the years 1981/82 (calibration period), 1986/87 and 1988/89 (verification period).

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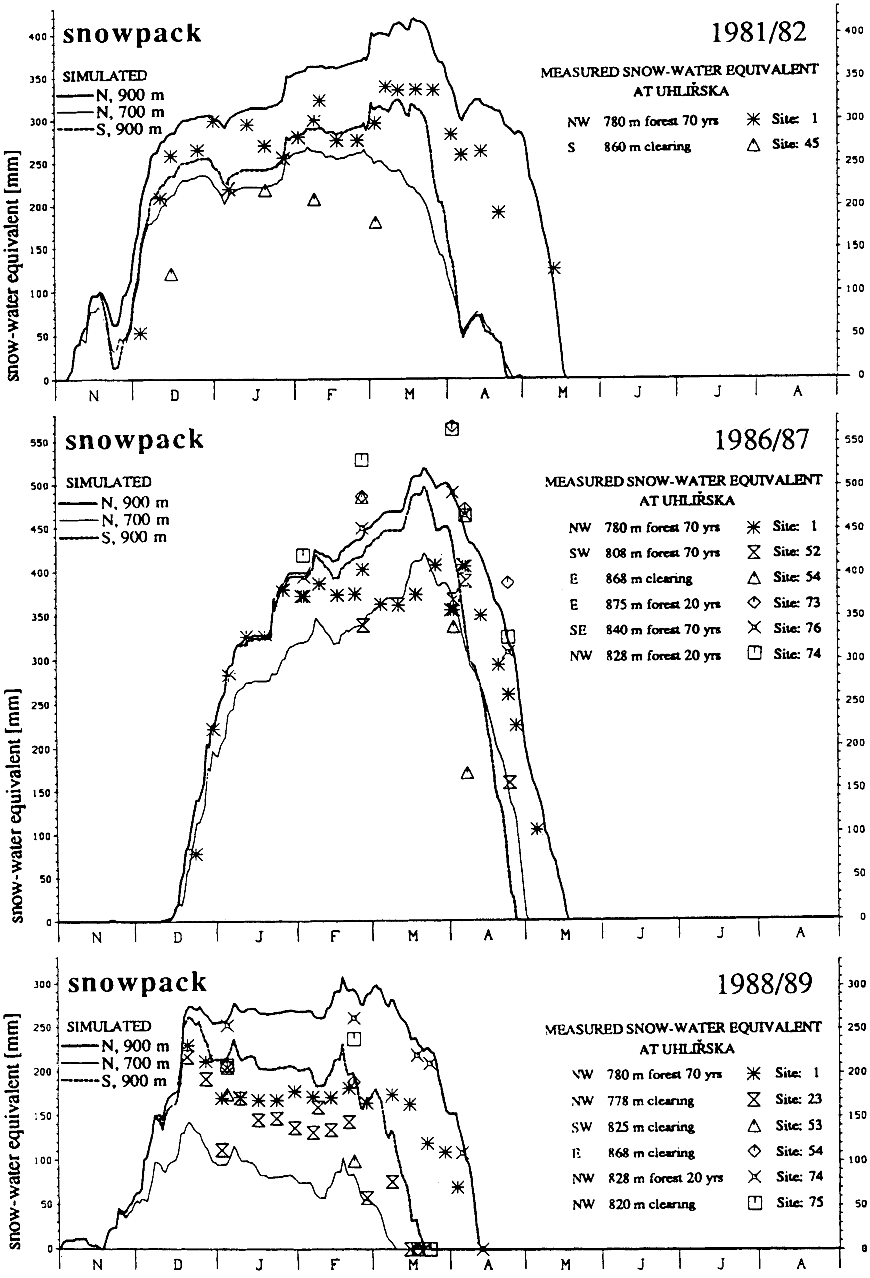

Fig. 7. Calculated snow-water equivalent at 900 m a.s.l. for aspect north in the Uhlířská basin for the years 1981/82 (calibration period), 1986/87 and 1988/89 (verification period) and comparison with measured values.

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In Fig. 7 simulated snow storage is compared with measured values. Site 1 (780 m a.s.l.) with complete observations faces north-west and is forested (70 year-old forest). The measured snow-water equivalents lie well between the computed values for 700 and 900 m and northern aspect, however, melt rates are somewhat overestimated. The measured snow-water equivalent at site 45 (clearing) facing south (860 m a.s.l.) are consistently lower than modelled values (900 m, aspect south) in winter 1981/82.

Additional snow measurements taken in later years allow a more detailed evaluation. In the year 1986/87 several sites with forest and different expositions can be compared. The sites 73 (875 m, east exposition, 20 year-old forest), 74 (825 m, north-west, 20 year-old forest) and 76 (840 m, forest 70 years, south-east) correspond well with the simulation for aspect north at 900 m. For comparison purposes, data from site 54 (east, 865 m), a clearing corresponding to site 73, are also given.

In the first half of December 1988/89 when the snowpack was built up, the transition between rain- and snowfall took place mostly between 700 and 900 m. As a result a strong snow accumulation gradient can be observed (more than twice as much snow fell at 900 m as compared to 700 m). Four sites representing clearings are shown: 23 (775 m, north-west), 53 (825 m, south-west), 54 (870 m, east) and 75 (820 m, north-west). Their melt curves fit surprisingly well to the simulated one for aspect south. Sites 1 and 74, both with forest and aspect north-west, are also plotted for the sake of comparison. Site 74 is in good agreement with the simulation (900 m, aspect north), while calculated melt rates at this elevation and aspect are higher than observed at site 1.

Discussion and Conclusions

This study shows that some structural changes of an operational precipitation-runoff model were necessary so that it could be applied to a basin exhibiting a complex karst-related hydrologic behaviour.

The HBV-ETH model functions well, not only in the alpine area with snow cover in the upper zones lasting several months, but also in much lower elevations where snow can melt away completely any time during winter.

In the Uhlířská basin (1.87 km^2, 775-885 m a.s.l.) the effect of the presence and the age or absence of forest on the development of snow-water equivalent was obviously as important as the effect of aspect and altitude. The observed melt of the snowpack at the forested sites agreed reasonably well with the modelled snowpack melt for the respective elevations and aspects. The maximum measured snow-water equivalents (in some years higher than the modelled ones) were attained at sites with younger forest (20 years old). The snowpack in clearings at the beginning of the season is generally as large as at the respective (paired) forested sites, but declines more rapidly and disappears about three weeks earlier. The smallest snow-

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pack and quickest melt was observed in a clearing with southern aspect, even though site elevation was comparatively high. Up to now, aspect was taken into account in the snowmelt function via the REXP parameter, however, the results here show, that vegetation cover needs to be considered as well. It is suggested to investigate appropriate parameterizations and their effect on discharge simulation.

As far as the effect of deforestation in the Uhlířská basin is concerned, a similar but less pronounced increase in runoff after clearcutting is observed as described by Křeček and Zelený (1980) and Miţă (1980) for similar physiographic settings, and Brandt *et al.* (1988) in a case study in Sweden. It would be of further interest to determine whether increased discharge is due to the reduced interception and evaporation losses. Furthermore, one would expect higher values of the melt factor like in the Swedish study, where several free model parameters, among them the degree-day factor, needed recalibration after felling of the forest.

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