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Priestley-Taylor Evapotranspiration in HBV-Simulations

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Estimations of potential evapotranspiration as input to runoff calculations with the HBV model are usually given as monthly standard values calculated with the Penman method. Daily changes in the weather conditions can in later model versions be taken into account by the introduction of a temperature anomaly correction of the evapotranspiration. In this study daily values of potential evapotranspiration calculated with the Priestley-Taylor method were used as input to the model. The required net radiation estimations were calculated from routine weather observations including cloudiness. Potential evapotranspiration was calculated on a three hour basis over a 20-year period. Model simulations using different input data on the potential evapotranspiration were made for three drainage basins (3,500-4,300 km^2) in Sweden. The Priestley-Taylor evapotranspiration generally gave small improvements of the runoff simulations. The simple temperature anomaly correction method gave improvements of the same size.

Introduction

Evapotranspiration is a main element of the annual water budget in Sweden. In southern parts of the country more than half of the precipitation returns to the atmosphere as evapotranspiration. This study focuses on the computation of evapotranspiration in the HBV model and forms part of a major revision of the model structure of the original HBV model (Bergström 1976). The revision has led to the development

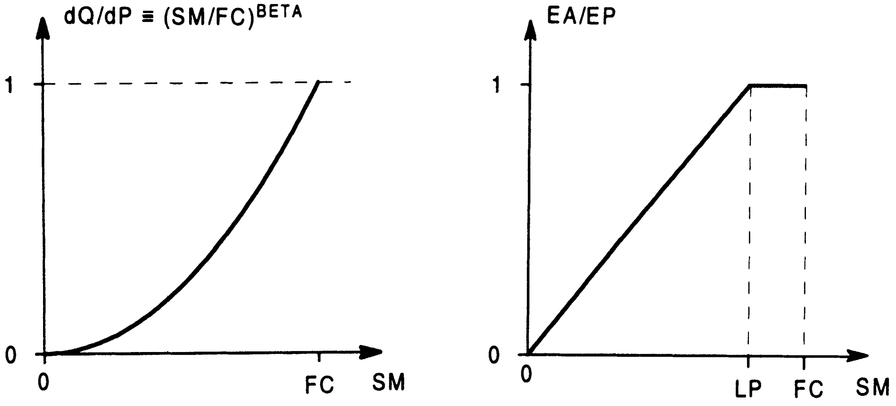

Fig. 1. Soil moisture routine of the HBV model. Relation between contribution to runoff (*dQ*) from rainfall and snow melt (*dP*) at different soil moisture values (*SM*), left, and relation between actual (*EA*) and potential evapotranspiration (*EP*), right. *FC*, *LP* and *BETA* are calibrated model parameters.

of a new model version, HBV-96, described thoroughly by Lindström *et al.* (1996a) and in a shorter version by Lindström *et al.* (1996b).

The soil moisture routine is one of the most important parts of the HBV model as it controls the volume of runoff. The routine is governed by two simple relations with three parameters, *BETA*, *LP* and *FC*, as shown in Fig. 1. *FC* represents the maximum soil moisture storage. *BETA* controls the contribution to runoff from rainfall and snow melt. *LP* is the soil moisture limit above which evapotranspiration reaches its potential value and below which it decreases linearly.

The parameter values are determined by calibration of the model, in which the computed and recorded hydrographs are compared. The quality of a model simulation is here judged by the commonly used R^2 value (Nash and Sutcliffe 1970). Monthly estimates of potential evapotranspiration are used as input data for the soil moisture routine of the original HBV model. In Sweden long-term mean monthly values by the Penman formula (Penman 1948), made by Eriksson (1981) or Wallén (1966), are usually used.

The evapotranspiration routine in the HBV model was further developed by Lindström and Bergström (1992). They introduced a simple parameter, *ETF*, to account for deviations in temperature from normal conditions. The long-term mean potential evapotranspiration is thereby reduced when it is colder than normal and increased when it is warmer than normal (Fig. 2). This simple routine led to improvements of the model simulations during cold summers (see *e.g.* Lindström *et al.* 1994).

Different attempts have been made to improve the evapotranspiration routine in the HBV model, by for example Andersson (1992) and Tallaksen *et al.* (1992). A simplification of the Thornthwaite temperature index method, including a seasonal-

Fig. 2. *ETF* routine for the temperature anomaly correction of potential evapotranspiration. *Ep* ≡ long-term mean potential evapotranspiration, *Ep* = corrected potential evapotranspiration, ΔT = temperature deviation from long-term mean, *ETF* ≡ model parameter.

ly varying coefficient has been used in the Nordic HBV model version for climate change studies described by Saelthun (1996).

Interception has originally been neglected or considered part of the snowfall correction and soil moisture accounting in the HBV model. This simplification has to some extent been compensated by the use of uncorrected precipitation data. A simple interception routine for forested areas was tested within the Nordic study on climate change and was later introduced as an option in the HBV-96 model. The tests with this interception routine did not, however, show any improvement of the model performance when used on a daily basis.

The Priestley-Taylor method (Priestley and Taylor 1972) was recommended, particularly for comparison purposes on a regional scale, by the Nordic seminar on evapotranspiration modelling in climate studies (Tallaksen and Anker Hassel 1992). In comparison with the more complex Penman-Monteith method (Monteith 1965) the relatively simple Priestley-Taylor method was suggested for the HBV model to balance this models general requirement for simplicity and modest data demand. Evapotranspiration calculated with the Priestley-Taylor method is primarily based on net radiation. Differences in aerodynamic and surface resistance are not taken into account, and the methods relevance for forested areas has therefore been questioned (Shuttleworth and Calder 1979). Nevertheless, the method has been widely used and was earlier tested in the HBV model for basins in northern Sweden by Evremar (1994). In the present study the method was also tested in basins in southern Sweden where evapotranspiration is more important. The objective was to develop and test a method for application of the Priestley-Taylor method on a daily basis in the HBV model and to test whether the model simulations could be improved by the use of this method. The study focused on estimation of discharge in large basins used for routine simulations and with normally available meteorological data.

Methods

The potential evapotranspiration, *EP*, was formulated by Priestley and Taylor (1972) as

$$EP = \alpha \frac{s}{s+\gamma} (R_n - S) \qquad (1)$$

R_n – net radiation
S – soil heat flux
γ – psychrometric constant
s – slope of the saturation vapour pressure curve
α – empirical coefficient

The Priestley-Taylor equation can be seen as a semi-empirical form of the Penman formula. It includes the empirical coefficient α which is site-specific. Priestley and Taylor obtained values of α, for diverse well-watered surfaces, between 1.08 and 1.34 with an overall mean of 1.26. This value has been commonly used and has been verified in various studies (*e.g.* Stewart and Rouse 1976; Stagnitti *et al.* 1989). Other studies have shown differing results *e.g.* Mc Naughton and Black (1973). De Bruin (1983) showed that the α value was related to the soil water content. Owe and Van de Griend (1990) used a dynamic α value in a modified Priestley-Taylor concept and found α values of up to 1.4. The value of α was in the present study determined by calibration of the HBV model.

The net radiation, R_n, can be estimated from measurements of global radiation (see *e.g.* Evremar 1994). These measurements are, however, only available for a few places in Sweden. In this study, the net radiation was therefore estimated using a method developed by Nielsen *et al.* (1981), who established regression equations by extensive comparisons between measurements of net radiation and cloud coverage. Cloud coverage is expressed as a value between 1 and 8, which relates to the cloud covered fraction of the sky. The Nielsen method uses the so called modified cloud coverage, N_m, which for high clouds is determined from the observed cloud coverage, N, as follows

$$N < 3 \Rightarrow N_m = N$$
$$N = 3 \Rightarrow N_m = N-1$$
$$N > 3 \Rightarrow N_m = N-2$$

For low clouds no adjustment of the observed cloud coverage is made.

Daytime net radiation is calculated as

$$R_n = a_0(N_m) + a_1(N_m)\sin(q) + a_2(N_m)\sin(q)^3 \qquad (2)$$

Night-time net radiation is calculated as

$$R_n = a_0(N) + a_1(N)\,U_{2m} + a_2(N)\,U_{2m}^2 + a_3(N)\,T^6 \quad (\text{if } N < 4) \qquad (3)$$

$$R_N = b_0(N_m) \quad (\text{if } N \geq 4) \qquad (4)$$

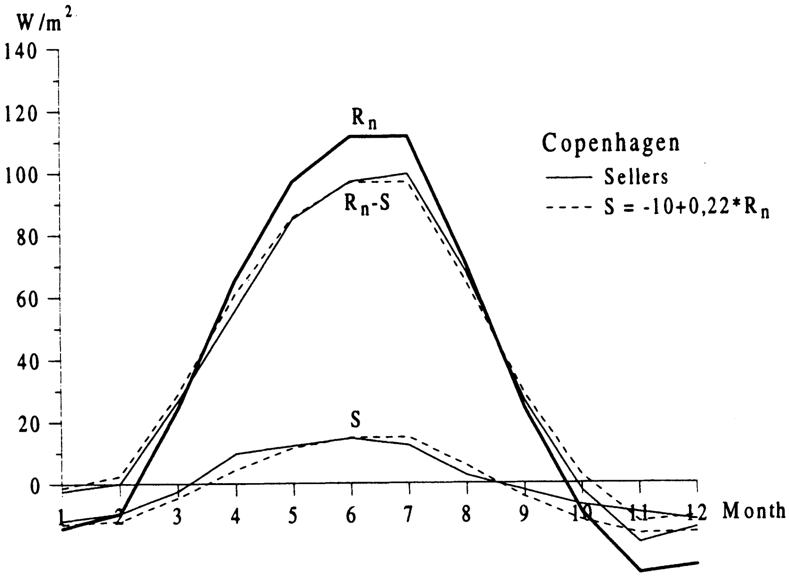

Fig. 3. Comparison between soil heat flux (S) for Copenhagen reported by Sellers (1965) and soil heat flux computed by the simplified method applied in this study using the net radiation (R_n) reported by Sellers.

R_n – net radiation
q – solar elevation
U_{2m} – wind speed at 2m
T – temperature at 2m
a_o, a_1, a_2, a_3, b_0 – empirical constants given by the Nielsen method as functions of N and N_m

The Priestley-Taylor equation includes the soil heat flux, S. This storage of energy in the soil is usually disregarded in practical applications. A simple attempt was here made to include it, by using a linear relationship between heat flux and net radiation, similar to the one shown by *e.g.* Deheer-Amissah *et al.* (1981). By assuming the annual soil heat flux to be zero, the heat flux was approximated to $S = -10 + 0{,}22 \cdot R_n$ for the stations included in the study. This is a very simplified method which does not fully take into account the asymmetrical seasonal soil heat fluxes observed in northern countries. Nevertheless, the method gave an approximation of the soil heat flux which was found to be satisfactory for this study and provided an obvious improvement of the net radiation estimation as compared to neglecting the influence of the soil heat flux. A comparison between soil heat fluxes estimated with this simple method and the fluxes reported for Copenhagen by Sellers (1965) illustrates the method (Fig. 3).

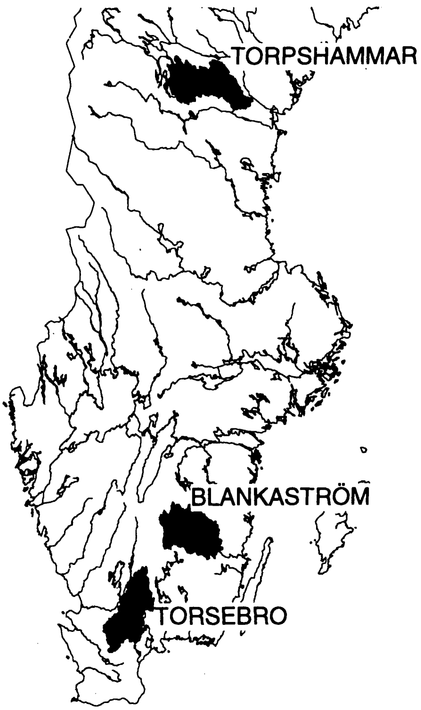

Fig. 4. Geographical location of the basins under study.

Data Base

Simulations with the HBV model and the Priestley-Taylor method for potential evapotranspiration were made for three basins in Sweden (Fig. 4). The basin areas and the forest covered fraction of the basins are given in Table 1. The model was calibrated for a 10-year period and another 10-year period was used for an independent verification. A comprehensive data set based on weather observations every three hours from two stations in or near each basin was used for computation of potential evapotranspiration. These computations were made with a time step of three hours, and the results were thereafter converted to daily values and weighted according to distance for use in the HBV model.

Table 1 – Data base for the HBV model simulations.

Basin	Area (km^2)	Lake area (%)	Forest area (%)	Calibration period	Verification period
Torsebro	3,676	9	59	1969-1979	1979-1989
Blankaström	3,446	7	72	1982-1992	1969-1979
Torpshammar	4,291	10	74	1979-1989	1969-1979

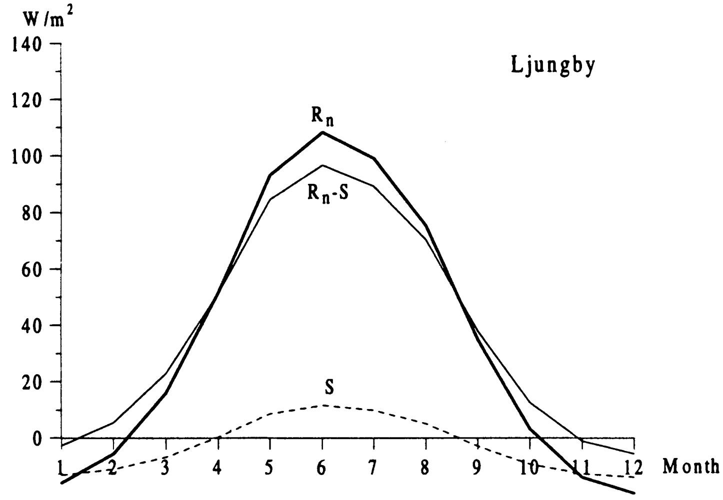

Fig. 5. Computed monthly mean values over a 20-year period for net radiation (R_n) and soil heat flux (S) for the synoptic station at Ljungby.

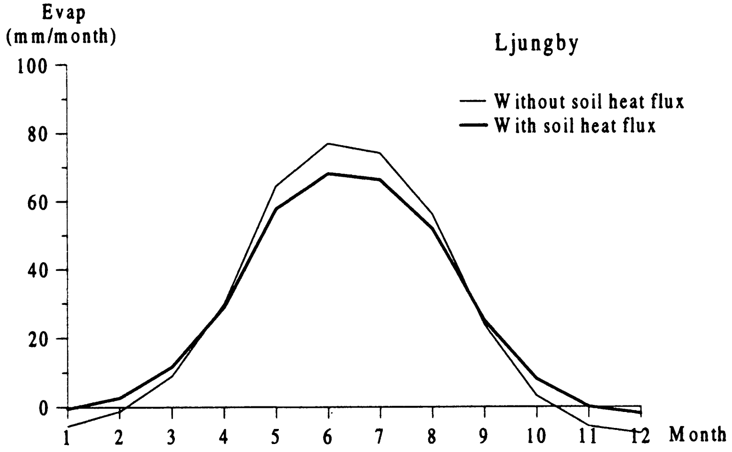

Fig. 6. Computed monthly mean values over a 20-year period for potential evapotranspiration estimated according to the Priestley-Taylor method with and without soil heat flux for the synoptic station at Ljungby.

Results

An example of the computed net radiation and soil heat flux over the year for one of the stations used in the study is shown in Fig. 5. The effect on the computed potential evapotranspiration from the introduction of the soil heat flux is illustrated in Fig. 6. Even though the method for soil heat estimation is very simplified and does not

Table 2. R^2 for calibration and verification periods for the three basins.

	Penman		Priestley-Taylor			
	Original model	With EFT	Without soil heat flux		With soil heat flux	
			With neg.	Without neg.	With neg.	Without neg.
Torsebro Cal. 69-79	0.932	0.934	0.926	0.934	0.934	0.935
Torsebro Ver. 79-89	0.865	0.880	0.861	0.875	0.875	0.880
Blankaström Cal. 82-92	0.833	0.842	0.793	0.833	0.823	0.834
Blankaström Ver. 69-79	0.902	0.881	0.830	0.888	0.881	0.886
Torpshammar Cal. 79-89	0.904	0.915	0.908	0.914	0.911	0.913
Torpshammar Ver. 69-79	0.886	0.888	0.886	0.893	0.891	0.896

fully take into account the seasonal variations, an improvement of the calculated evapotranspiration is observed where large parts of the otherwise computed negative values during the winter are avoided. The seasonal variation of the evapotranspiration calculated according to the Priestley-Taylor method was found to be quite similar to that of the long-term monthly mean values calculated with the Penman formula by Wallén (1966) and Eriksson (1981), earlier used in HBV model applications in Sweden.

For each basin six simulations were made for each of the calibration and verification periods (Table 2). Two simulations were made using monthly mean values for potential evapotranspiration according to the Penman formula. The first of these corresponds to the situation in the original HBV model and the second one uses the temperature correction parameter *ETF* and thus produces daily estimates of potential evapotranspiration. The other four simulations were made using daily potential evapotranspiration according to the Priestley-Taylor equation. In two of these the soil heat flux was disregarded and in the two others the soil heat flux was treated as described above.

Negative evapotranspiration values, *i.e.* condensation, occurred during winter, especially when the soil heat flux was not taken into account. Two simulations were made in which the condensation was set to zero. The negative values obtained by the Penman formula for winter months have also usually been set to zero in previous applications of the HBV model. Since the evapotranspiration in the HBV model is assumed to be zero when the ground is covered by snow, the treatment of the condensation calculated with the Priestley-Taylor method during this period is less important for the model simulation. Slightly higher R^2 values were obtained when no negative values of evapotranspiration were accepted and only these simulations of Priestley-Taylor evapotranspiration were hereafter studied. The specific interception routine of the HBV model was not used for any simulation.

The α values were for the three basins calibrated to values between 1.49 and 1.76 with a mean value of about 1.6. These values are considerably higher than what is usually reported. Owe and Van de Griend (1990) used a dynamic value of α and

Table 3. Mean annual potential evapotranspiration calculated with the Priestley-Taylor method for 6 stations, compared to the Penman values calculated by Eriksson (1981) and Wallén (1966) for the same stations or for other stations in the region (in italic).

	Mean annual potential evapotranspiration (mm)		
Station	Priestley-Taylor (1968-93)	Penman (by Eriksson) (1961-78)	Penman (by Wallén) (1931-60)
1. Ljungby	501	607	
Växjö		580	470
2. Osby	517	497	
Växjö		580	470
3. Målilla	566	551	
Västervik		578	537
4. Nässjö	513	536	
Jönköping		569	466
5. Hunge	379		
Östersund		506	462
6. Fränsta	406	425	
Östersund		506	462

found daytime values of up to 1.4. They also suggested that on 24-hour calculations the value could be even higher still. Despite the high α values obtained in the present study, the computed potential evapotranspiration agreed reasonably well with the values calculated with the Penman formula by Eriksson (1981) and Wallén (1966). A comparison of the annual Priestley-Taylor values of potential evapotranspiration and the values reported by Eriksson and Wallén are given in Table 3. For the stations in southern Sweden (No. 1-4), the Priestley-Taylor values are mostly between the estimations of Eriksson and those of Wallén, while the values for the northern stations are lower than both the Eriksson and the Wallén estimations.

The introduction of the temperature correction parameter *ETF* gave improvements for all simulation periods but one (the verification period in Blankaström), compared to the standard model. The simulations with the Priestley-Taylor evapotranspiration were usually better when the soil heat flux was used than when it was disregarded. The simulations with the Priestley-Taylor evapotranspiration with soil heat flux but without condensation gave higher R^2 values than the original model in five out of six simulation periods. The Priestley-Taylor method performed better than the simple *ETF* correction in three of the periods. The improvements were, nevertheless, small. The largest improvement was obtained in the verification period for Torpshammar, in which the R^2 increased from 0.888 to 0.896.

The differences in R^2 for the long simulation periods are thus small. The simulated discharges are also quite similar during most years. There are, however, noticeable differences during some periods. Fig. 7 shows three different runoff simulations and computed evapotranspiration for Torpshammar 1987. Soil heat flux is included

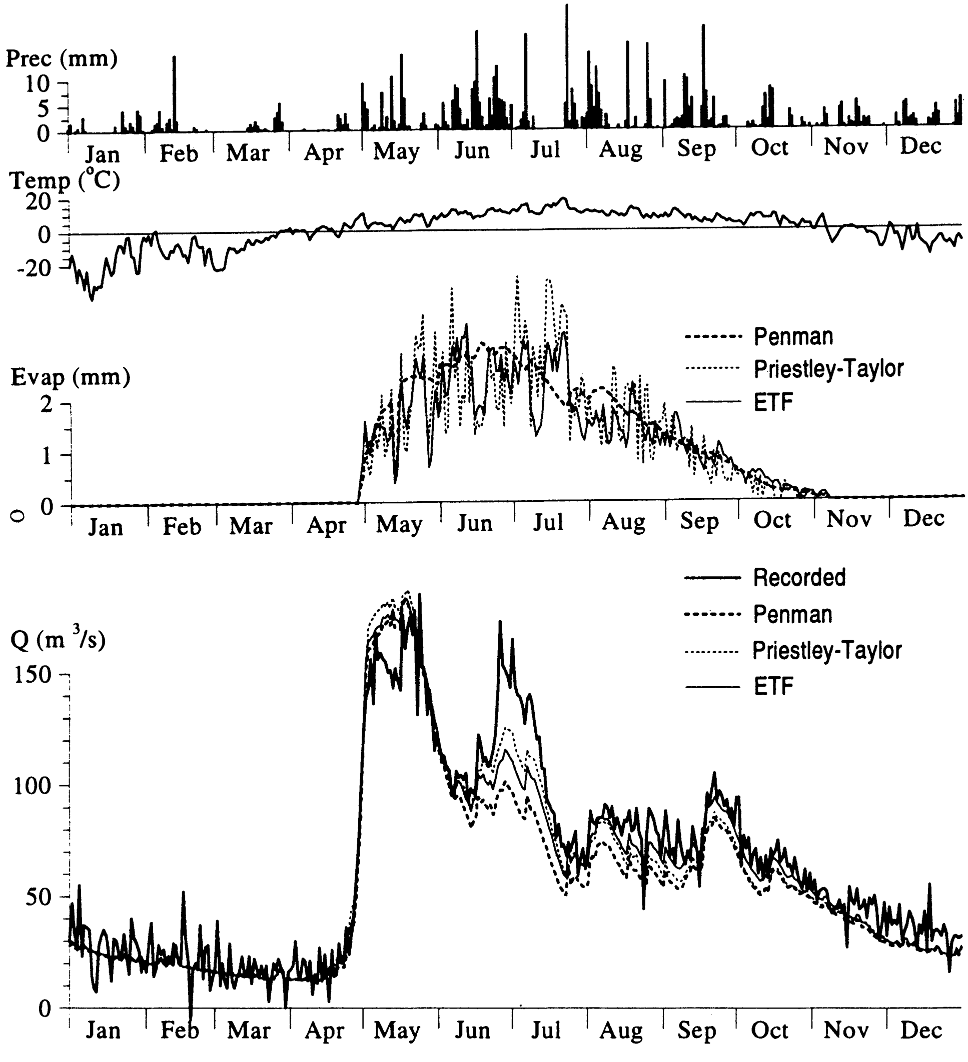

Fig. 7. Computed actual evapotranspiration by the Penman monthly mean values, the *ETF* correction and the Priestley-Taylor method (negative values not accepted, soil heat flux included), together with the computed discharge (*Q*) by the three methods compared to the recorded discharge at Torpshammar 1987.

in the Priestley-Taylor simulation. No negative values of evapotranspiration are accepted. The day to day variation in the Priestley-Taylor and *ETF* simulations is quite different from the monthly mean Penman values of the original model. There are also periods when the Priestley-Taylor evapotranspiration and the *ETF* evapotranspiration differ considerably, for example during June and July of 1987. During this

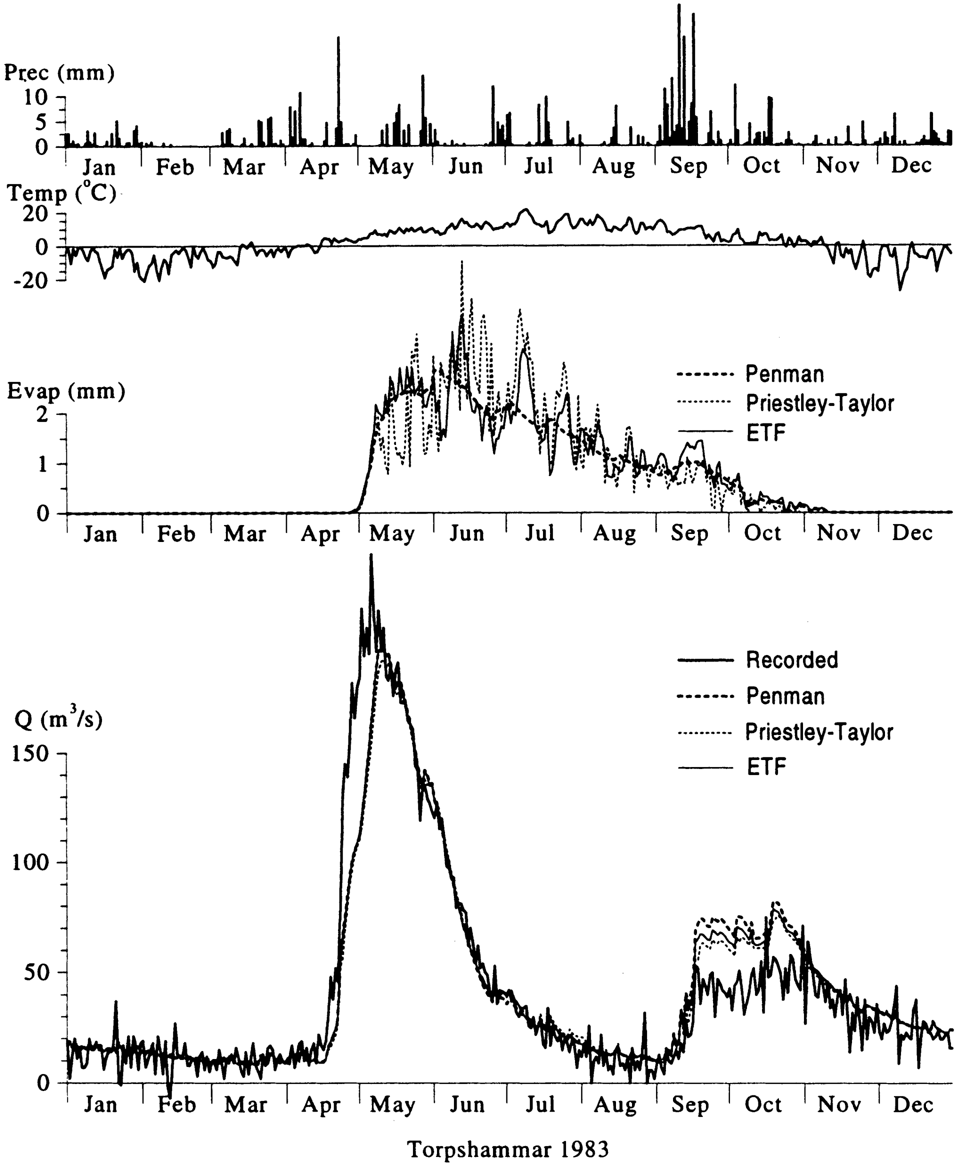

Fig. 8. Computed actual evapotranspiration by the Penman monthly mean values, the *ETF* correction and the Priestley-Taylor method (negative values not accepted, soil heat flux included), together with the computed discharge (Q) by the three methods compared to the recorded discharge at Torpshammar 1983.

unusually cool summer the runoff was underestimated by the original model since the Penman standard values gave a too high evapotranspiration. Both the simulations by the Priestley-Taylor method and the *ETF* correction here gave a significant improvement. The *ETF* correction gave better results than the Priestley-Taylor method during late summer and autumn, while the Priestley-Taylor method gave better results during the early summer.

Fig. 8 shows the corresponding model simulations for 1983. The discharge during the autumn was here considerably overestimated by the HBV model. A small improvement was obtained by the *ETF* correction. However, the best results were obtained by use of the Priestley-Taylor evapotranspiration. This method gave a higher evapotranspiration than the *ETF* method during the summer, which resulted in a lower soil moisture storage at the arrival of the autumn rainfall.

Discussion and Conclusions

The use of the Priestley-Taylor method for calculation of evapotranspiration generally resulted in small improvements of the runoff simulations by the HBV model. The R^2 values of the original model simulations were generally high and further large improvements are generally difficult to achieve. Improvements of the same size as for the Priestley-Taylor method were achieved by use of the simple temperature anomaly correction method, *ETF*.

The main objective of this work was to test whether the HBV model could be improved by the use of the Priestley-Taylor method for estimation of evapotranspiration. In principle, the method should be superior to the monthly mean values which have traditionally been used. In practice, however, the estimation of evapotranspiration by the more correct method may suffer from difficulties in obtaining the input data, *e.g.* the net radiation, with the required resolution in time and space. Similar improvements were thus obtained using the much simpler *ETF* method. Since the HBV model was calibrated to the observed runoff data, errors in the estimation of evaporation are compensated by other parameters in the calibration process. If the objective had been to evaluate the reasonableness of different evapotranspiration methods, a comparison with measured evapotranspiration would have been preferable. Such measurements are, however, very rare, at least in Sweden. The use of a water balance model in well controlled basins, with reliable estimates of precipitation and runoff, could be a complement since this provides an independent alternative for estimation of evapotranspiration by the water balance method.

The Priestley-Taylor method demands data on net radiation at a high resolution in time. These data can presently only be obtained from a small number of stations or from calculations based on meteorological routine observations. These computations introduce a much higher level of complexity than what is used in the rest of the HBV model. The results do not presently justify an operational use of the Priestley-Taylor method in the HBV model. In special applications, however, for example studies of climate change, the more physically based method should be preferable.

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