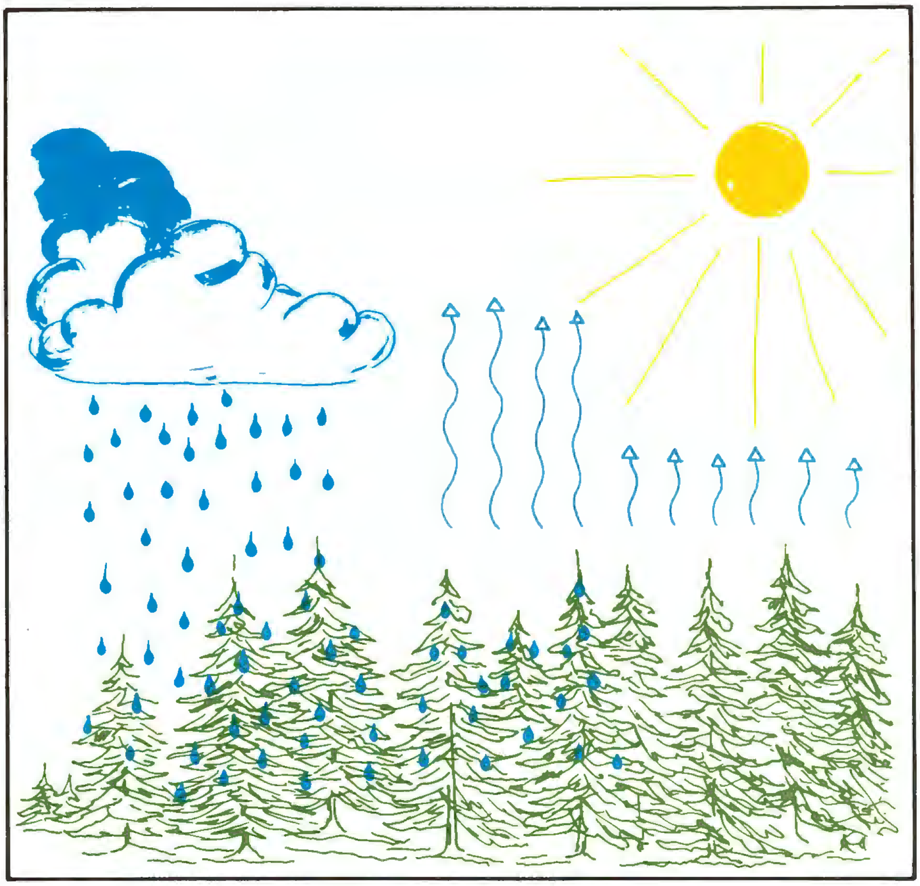

A FOREST EVAPOTRANSPIRATION MODEL USING SYNOPTIC DATA

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Abstract A model giving daily actual evapotranspiration values from synoptic data has been developed using results from the forest meteorological measuring site Velen in southern Sweden. The following submodels are included:

- Model for evaporation of rain water intercepted by the forest canopy. Parameters are the free throughfall coefficient and water storage capacity of the canopy. The model was developed using rainfall data from 29 troughs sited below and aside the canopy.
- Model for transpiration from the dry forest canopy. A physiological expression for the canopy surface resistance has been developed using 52 daily transpiration values obtained over the canopy by the Bowen ratio-energy balance method.

Using data from seven synoptic stations during seven warm seasons (April - October) monthly model evapotranspiration sums were compared to monthly data estimated from the hydrological water balance. The agreement was much better than using the traditional Penman formula with synoptic data. Thus, modelling of the special forest processes gives significant improvement of the monthly values. The model can now be run for about 190 synoptic stations in Sweden and comparisons can be made with evapotranspiration measurements made in other parts of the country.

Key words
Evapotranspiration
Actual evapotranspiration
Forest meteorology/hydrology
Synoptic data
Rain interception
Surface resistande/conductance
Water balance
Penman formula

Supplementary notes
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Kyllikille

1. INTRODUCTION

Methods to use routine observations from synoptic weather stations to determine evapotranspiration from natural surfaces have been developed and used earlier. Mostly the so-called Penman formula has been used. Since this formula was developed for a standard water or grass surface most attempts for other types of surfaces cannot be expected to give adequate results.

Nevertheless, the Penman formula has been used to estimate potential evapotranspiration for larger areas of mixed composition using data from the synoptic tic network. Examples for Sweden of such application have been presented by Wallén (1966) and Eriksson (1981). Thom and Oliver (1977) showed that the Penman formula can be properly applied to natural surfaces only after some revision.

The principles of forest evapotranspiration are very different from those of low vegetation. These principles have earlier been applied to a real forest in Sweden (Jädraås) by Halldin and Grip (1979). In this report a model will be developed that can use routine synoptic observations to evaluate forest evapotranspiration on a daily basis.

It has been considered very important to treat forest surfaces separately because they cover as much as 55% of Sweden . In Sweden two special scientific forest meteorological measuring projects have been performed, one in the Velen hydrological research basin by the SMHI and the second one in Jädraås in the middle of Sweden by the Swedish Coniferous Forest Project.

This report will use the results of the measurements in Velen and some foreign research results.

In short the steps of developing the model for forest evapotranspiration (ET) will be:

- Develop the formal model computation procedures from specific properties of forest canopies.

- Adapt the model and its parameter values using daily values of ET evaluated by the Bowen ratio-energy balance method and measurement of rain interception - both data obtained at the Velen forest site in 1973 and 1974.

- Test the model against independent monthly ET-values evaluated by the water balance method in the Velen area during 1967-74.

2. PRINCIPLES OF FOREST EVAPOTRANSPIRATION

The model development to be described in the following sections is based on so-called Monteith equation. Calder (1977) gives a brief and excellent presentation of this equation and some of his text will be quoted here (with a change of a symbol):

' Hydrologists are often required to estimate evaporation losses from crops both in studies of irrigation schemes and for predicting the effects of a land use change as part of a water resource study. The Penman (1948) equation provides a simple and practical method for estimating losses from grass and short crops, given basic meteorological variables, and has proved reliable over a wide range of environmental conditions. However, this equation is not suitable for application to tall crops such as forests whose aerodynamic and surface resistances are likely to be very different from grass. (The Penman equation will be discussed further in section 6.2.2, with numerical examples.) A modified version of the equation (Thom and Oliver, 1977) or the more general form of the equation given by Monteith (1965) which requires more detailed measurements of the meteorological variables, should then be used. For practical purposes the Monteith equation, although theoretically capable of giving accurate estimates of evaporation loss from any crop, is seldom used. Usually this is not because of a scarcity of the necessary meteorological data, which are becoming increasingly available from reliable automatic weather stations, but because of lack of knowledge of the crop aerodynamic and surface resistances.

Monteith (1965) showed that the latent heat flux from any surface could be expressed as:

$$\lambda E = \frac{\Delta R_n + \rho c_p (e_s - e)/r_a}{\Delta + \gamma(1 + r_s/r_a)} \qquad (W\ m^{-2})$$

where

E	= vapour flux	$(kg\ m^{-2}\ s^{-1})$
γ	= psychrometric constant	$(kPa\ {}^{o}C^{-1})$
λ	= latent heat of vaporisation	$(J\ kg^{-1})$
Δ	= slope of the saturation vapour pressure curve ($=de_s/dT$)	$(kPa\ {}^{o}C^{-1})$
R_n	= net radiation	$(W\ m^{-2})$
ρ	= density of air	$(kg\ m^{-3})$
c_p	= specific heat of air	$(J\ kg^{-1}\ {}^{o}C^{-1})$

r_a is the aerodynamic resistance to the transport of water vapour from the surface, at an unknown vapour pressure e_o, to some reference level above, where the vapour pressure is known to be e, defined as:

$$r_a = \frac{\rho c_p}{\gamma} \frac{(e_o - e)}{\lambda E} \ (s\ m^{-1})$$

and r_s is the resistance to the transport of water vapour from some region within or below the surface at a water vapour pressure, e_{so}, to the surface itself defined as:

$$r_s = \frac{\rho c_p}{\gamma} \frac{(e_{so} - e_o)}{\lambda E} \ (s\ m^{-1})$$

Thus it is possible to calculate evaporation losses if the relevant meteorological data are available and if r_a and r_s can be estimated under the environmental conditions pertaining. If E is to be calculated for a forest over a time period which includes precipitation the problem reduces to:

(1) Developing a canopy interception model which will predict the length of time for which the canopy is wet, following precipitation, when r_s can be considered to be zero.

(2) Estimating r_s when the canopy is dry, when r_s is a purely physiological resistance and is likely to be a complex function of both past and present environmental factors.

(3) Estimating r_a.

The equation can also be used to estimate the canopy parameters r_a and r_s if values of E and the meteorological variables are available'.

It is the crucial point of the Monteith equation that the meteorological data used can be measured directly. Therefore e_s (saturation vapour pressure) and e (actual vapour pressure) both refer to some distance from the surface (at a reference level below or above the top of the vegetation) where they can be measured.

The symbol e_{so} (denoted incorrectly as e_s by Calder (1977) but changed to e_{so} in the quotation above) stands for vapour pressure within the surface (e g inside stomatal pores) where the air is saturated.

The Monteith equation has been discussed also by Bringfelt (1975). In the model to be developed here, the Monteith equation will be applied separately for the cases of dry forest (transpiration) and wet forest (evaporation of intercepted rain water).

During times of appreciable water loss from dry forest, the last term ($\rho c_p(e_s-e)/r_a$) dominates the numerator and in the denominator r_s/r_a is 10-50. Retaining only the last term in both numerator and denominator gives:

$$\lambda E \approx \frac{\rho c_p}{\gamma} \frac{e_s - e}{r_s}$$

(This can be obtained from the definition of r_s above by putting $e_{so} - e_o \approx e_s - e$ which is a good approximation for a dry forest). Thus, transpiration can be expressed as vapour pressure deficit in the free air at some level within or above the forest divided by the surface resistance. This simple relation was used in the Velen forest to derive expressions for the transpiration as function of vapour pressure deficit and global radiation. For the data of 1973 and 1974 r_s was found to depend on these two meteorological variables and not on soil water content. See Bringfelt (1982).

In a dry forest the canopy itself has to regulate the water loss*. In other case the forest would soon dry out due to the ability of the stirred air to take away the water vapour (low r_a).

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*This is made by the stomatal pores resulting in a stomatal conductance k_{sc}($m\ s^{-1}$) per unit area of transpiring surface. To obtain the surface conductance k_s of the whole canopy, k_{sc} has to be multiplied by the leaf area index, (LAI). The surface resistance is $r_s = k_s^{-1} = (k_{sc} \cdot \mathrm{LAI})^{-1}$.

For the case of wet forest r_s is near zero so r_a cannot be neglected. In the model a constant value for r_a is used throughout. Thus, following Thom and Oliver (1977) the evaporation from the completely wet forest is given by a constant multiplied by the vapour pressure deficit in the air.

The rate of evaporation from a wet forest is known to be of the order of three times as large as the rate of transpiration from the dry forest under the same weather conditions, see Stewart and Thom (1973). This illustrates the drastic difference between dry and wet canopy which holds for forest but not for grass. See also Calder (1979).

The details in application of these principles in the practical evapotranspiration model will be given in the following sections.

3. SITE AND MEASUREMENTS

The evapotranspiration during two summer seasons from a forest in the Velen area between the lakes Vänern and Vättern in Sweden was evaluated by the Bowen ratio - Energy Balance method. Hourly averages of radiation and profiles of temperatures and humidity were recorded continuously in a 54 m high meteorological mast (58.802^{O}N, 14.316^{O}E).See figure 1. These data were taken above the forest canopy. The vapour pressure deficit (VCD), to be used below, was taken at a height within the canopy: 16 m above ground.

The evaporation of rain water intercepted by the forest canopy was measured by rain collecting troughs sited in clearings and below the canopy.

The site is a flat area with a 60 years old forest of mean tree height 20 m. The stand is dense with nearly 1 500 trees per hectare with a leaf area index estimated as 5. The forest is mainly coniferous and the prevailing tree species are Picea abies 74%, Pinus silvestris 27% and Betula verrucosa 9%. The site and measurements have been described in detail by Bringfelt and Hårsmar (1974), Bringfelt and Orrskog (1976) and Bringfelt et al (1977). For data see also Bringfelt (1980).

For the Velen hydrological basin see section 6.2.1.

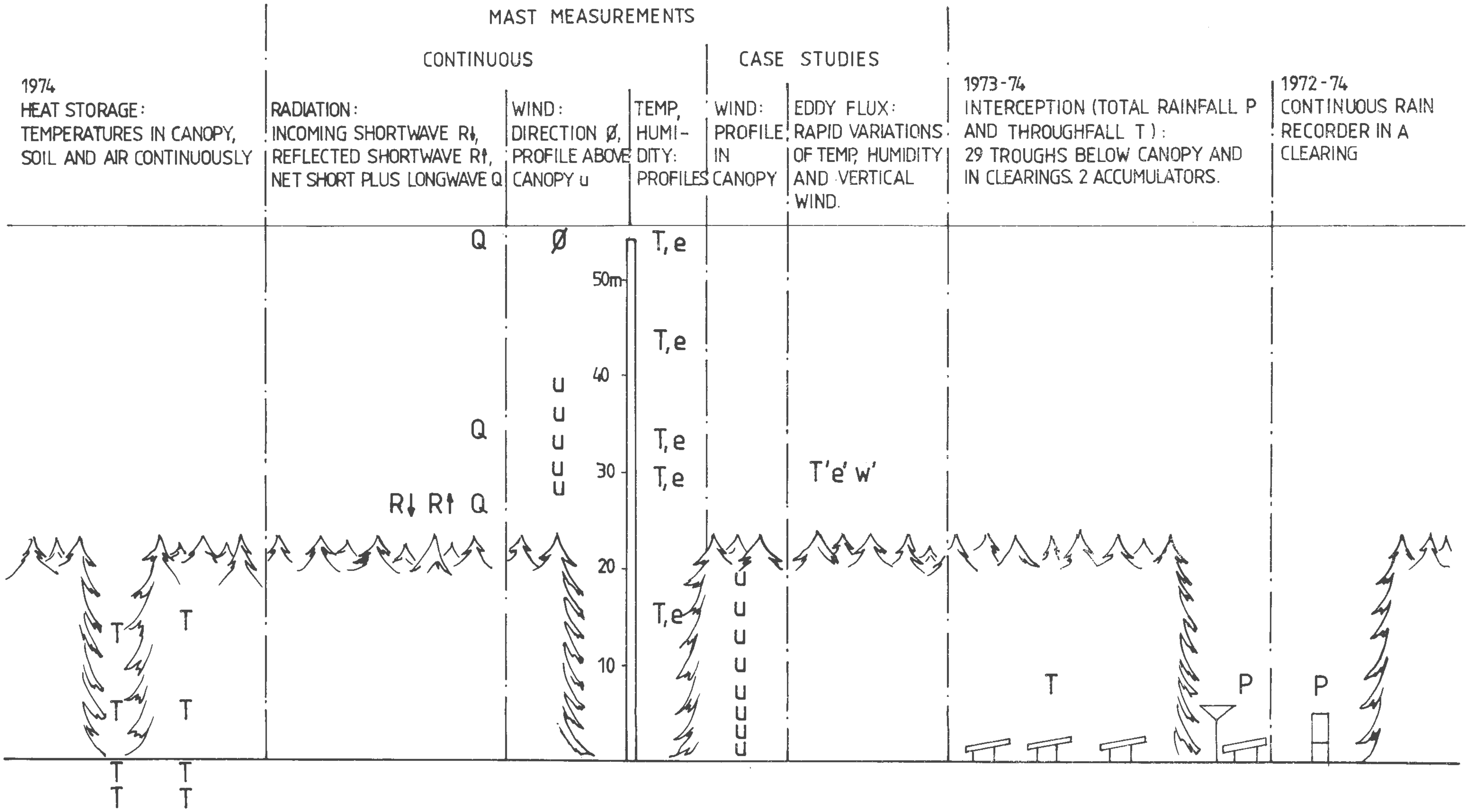


Figure 1 Measurements in and around the meteorological mast in Velen 1971-74.

4. MODELS USING INPUT DATA FROM THE SITE

This section will deal with the theory for a model of forest evapotranspiration and test it using input data from the measuring site in Velen.

Below will be given a symbol list and the model equations to be discussed in the following sections.

SYMBOL LIST

INTERCEPTION MODEL

Input variables

AR (AN)	daytime (nighttime) rainfall (mm)
$\overline{VCD}$	daytime average water vapour concentration deficit ($g\ m^{-3}$)
ASTR	astronomical daylength (hours)
NET	(alternative input variable) daytime net radiation (kWh/m^2)

Parameters

S	water storage capacity of forest canopy (mm)
$k = 1 - p$	where p is the free throughfall coefficient
A	time constant for the evaporation rate after rainfall ($mm\ g^{-1} m^{3} h^{-1}$)
M	rate of forest evaporation during rainfall (mm/hr)
T_U	rough storage capacity of ground and low vegetation (mm)

Derived variables

VR (VN)	duration of daytime (nighttime) rainfall (hours)
E_{RAIN}	daily evaporation during rainfall (mm)
E_D	daytime evaporation from a steadily saturated canopy (mm)
C--	water stored on the forest canopy (mm): at sunrise (C_{UP}), at start (C_{AM}) and end (C_{PM}) of daytime rainfall period, at sunset the preceding (C_{i-1}) and current (C_i) day
$E_C(E_U)$	daytime evporation from canopy (ground and low vegetation) (mm)
T_N (T_R)	throughfall during night (day) (mm)
EX	exponential reduction factor for the water stored on the forest canopy after nighttime or daytime rainfall

TRANSPIRATION MODEL

Input variables

$\overline{RIS}$	daytime average flux of global radiation (W m^{-2})
$\overline{VCD}$	daytime average water vapour concentration deficit (g m^{-3})

Parameters

a, b and c	(In Lohammar equation)

Constants

L	latent heat of vapourization (2500 Jg^{-1})

Derived variables

$\overline{E}$	daytime average transpiration flux (W m^{-2})
VR (VN)	duration of daytime (nighttime) rainfall (hours)
E_{TRA}	daily transpiration sum (mm)

MODEL EQUATIONS

INTERCEPTION MODEL

$$VR = MIN(ASTR, 7 \cdot {}^{10}log(1 + AR)) \quad (1)$$

$$EX = EXP(-A \cdot \overline{VCD} \cdot ASTR/2S) \quad (2)$$

$$E_{RAIN} = M \cdot VR \quad (3)$$

$$C_{UP} = MIN(S, C_{i-1} + k \cdot MIN(S/k, AN)) \quad (4)$$

$$C_{AM} = C_{UP} \cdot EX \quad (5)$$

$$C_{PM} = MIN(S, C_{AM} + k \cdot MIN(S/k, AR - E_{RAIN})) \quad (6)$$

$$E_C = \underline{(C_{UP} + C_{PM})(1 - EX) + E_{RAIN}} \quad (7)$$

$$T_N = AN + C_{i-1} - C_{UP} \quad (8)$$

$$T_R = AR - E_{RAIN} + C_{AM} - C_{PM} \quad (9)$$

$$E_U = \underline{MIN(T_U, T_N) + MIN(T_U, T_R)} \quad (10)$$

$$C_i = C_{PM} \cdot EX \quad (11)$$

TRANSPIRATION MODEL

$$\overline{E} = \frac{a}{(b + \frac{1}{RIS})(c + \frac{1}{VCD})} \qquad (12)$$

$$VN = MIN(24 - ASTR, 7 \cdot {}^{10}\log(1 + AN)) \qquad (13)$$

$$VR = MIN(ASTR, 7 \cdot {}^{10}\log(1 + AR)) \qquad (1)$$

$$E_{TRA} = \underline{\overline{E} \cdot MAX(0, ASTR - 0.5\ VN - 1.5\ VR) \cdot 3.6/L} \qquad (14)$$

4.1 Presentation of data

The data from the Velen site presented in the appendix summarize the data of theearlier measuring project. Data exist from 296 days in the warm seasons of 1973 and 1974. Complete data (with evapotranspiration values) exist for 127 of these days. The data are used here as input and test data to the models. The interception data are summarized in table 2.

4.2 Models for evaporation of intercepted rain water

Model for interception on the forest canopy

Theory

The model uses as daily input data:

- Rainfall during the preceding 12 nighttime hours and during the 12 daytime hours. (A 24 hourly sum can also be used, but it has to be split up into these two parts before entering the model).

- The sum of the hourly values of water vapour concentration deficit (VCD) over the daylight period.

The model was derived from an equation proposed by Rutter et al (1971/1972):

$$-\frac{dC}{dt} = \frac{C}{S} E_S$$

where S is the water storage capacity of the canopy and

C ($\leq$S) is current storage on the canopy,

E_S is the evaporation rate from the canopy when the storage is largest, i.e. equal to the capacity S. Then the evaporation rate $-\frac{dC}{dt}$ corresponds to current storage. The evaporation rate is assumed proportional to the amount of water stored on the canopy.

The model is based on the solution

$$C = C_o e^{-\frac{E_S}{S} t}$$

where the storage after one daytime is reduced by the factor $e^{-\frac{E_D}{S}}$.

For a wet forest canopy E_S is proportional to VCD, following Thom and Oliver (1977).

Summing over the daylight hours makes it possible to write

$$E_D = A \cdot \Sigma \text{ VCD} = A \cdot \text{ASTR} \cdot \overline{\text{VCD}}$$

(A dependence of E_D on net radiation $E_D = A \cdot$ NET has also been tested, see table 2.)

For day No. i the model equations 1 - 11 have to be used in that order. The model gives the evaporation during daytime neglecting nighttime evaporation.

The model calculates for successive days C_i and actual evaporation E_C and E_U (see underlined equations). Thus, C_i from the preceding day is used as C_{i-1} for the next day etc.

The calculations must be initialized on a day (i = 1) when $C_{i-1} = C_o = 0$, i.e. when the canopy is dry.

The model works on a daily basis, but there is some subdivision within each day. Thus, the daytime rainfall AR (mm) is taken to occur during VR of the daytime hours (see figure 2).

The model assumes that in the daytime evaporation will reduce water storage by the factor EX after a rainfall (equations 2, 5, 7 and 11). For practical reasons $\overline{\text{VCD}} \cdot$ ASTR is calculated also using values during the rainfall. Since VCD is then very small (table 1) the result will fairly well hold for the periods without rainfall as assumed in the model.

Equations 4 and 6 use definitions of S and k according to Bringfelt and Hårsmar (1974) to calculate the water stored on the canopy after a rainfall. In equation 6 the daytime rainfall amount AR is reduced by the evaporation E_{RAIN} estimated to occur during the rainfall.

For M (see eq. 3), the evaporation rate from the forest canopy during rainfall, the value 0.05 mm/h has been used.

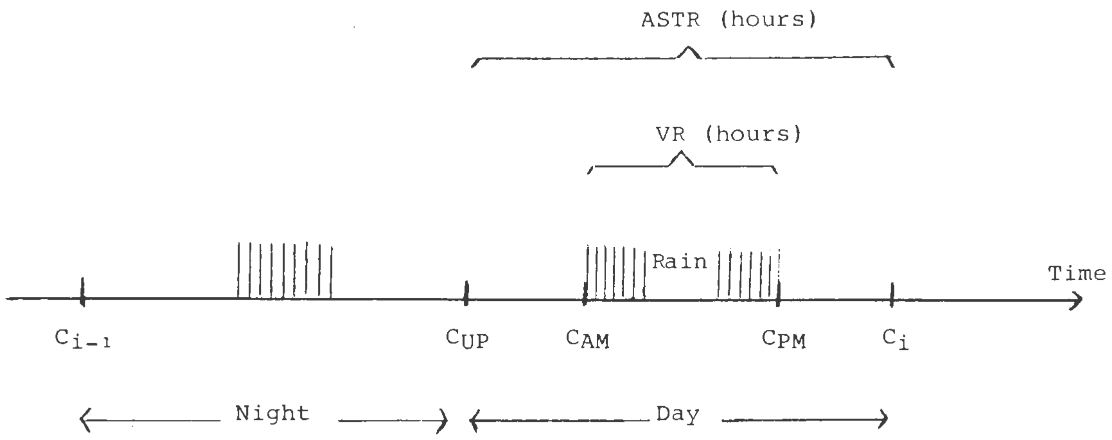


Figure 2 *Time intervals used in the model for daily evaporation of rain water intercepted on the forest canopy.*

This value was obtained directly from the mast measurements using the Bowen ratio - energy balance method for 18 daytime rainfall events during totally 73 hours, see table 1.

The rate was correlated to vapour concentration deficit, global and net radiation, rainfall rate and wind speed. The best coupling was found to radiation. The rate did only in one case exceed 10% of the rainfall rate. According to Thom (1979) such a rate requires that wet bulb depression and wind speed are high enough. No such coupling could be found in the Velen data and for simplicity just a fixed value of M will be used in the model.

In model operation, E_{RAIN} (the daily evaporation during rainfall) was obtained by equation 3, multiplying M by the rainfall duration VR.

Test of forest canopy interception model

The interception measurements available over periods of 3-30 days (average one week) will here be used to test the interception model developed.

The interception model is believed to relate interception to rainfall rather properly since the model has been developed and tested using data from the same type of gauge (i e troughs) both for input (rainfall in clearings) and output (interception on tree canopy). The measured data on interception in table 2 were calculated by subtracting rainfall in the troughs below canopy (throughfall) from rainfall in the troughs in clearings. See Bringfelt and Hårsmar (1974) and Bringfelt (1980) for a full discussion and complete data.

Table 1
Data obtained over the Velen forest for daytime rainfall periods

Date	Hours	VCD g/m^3	u m/s	RIS W/m^2	R mm/h	EB mm/h
730717	8 - 9	0.6	3	203	4	0.05
24	19 - 21	0.2	2.5	222	2	0.01
0804	15 - 18	0	3	179	3.5	0.07
08	6 - 12	0	5	138	1	0.07
0920	6 - 10	0.04	4	39	3	0.01
740529	15 - 18	0.2	3	206	0.8	0.07
30	7 - 8	0	3.6	346	0.5	0.08
0714	9 - 14	0.1	-	59	4.2	0.02
0810	11 - 14	0.6	2	81	5	0.14
11	16 - 19	0.4	2	176	4.4	0.02
15	7 - 11	0	3	66	0.6	0.03
16	16 - 20	0	3	181	1	0.01
27	18	0.3	4.5	237	10	0.003
0903	10 - 15	0.1	4.5	64	1	0.04
05	7 - 9	0.5	5	65	1.8	0.04
05	16 - 19	0.1	3	65	1	0.04
06	10 - 15	0	3	83	1	0.09
28	6 - 8	0	7	34	1	0.001

VCD = vapour concentration deficit, u wind speed, RIS global radiation, R rainfall rate, EB evaporation rate obtained by the Bowen ratio - energy balance method.

The average value of EB turns out to be 0.05 mm/h.

There were a total of 28 measuring periods in 1973 and 1974. However, the model has been run for only 14 periods made up by putting together some of the original periods. This was made so that each period starts by zero water storage, which was necessary to initiate the model, see above.

Table 2 shows the results from five versions of the model. The version 'extended rain' is the one described above assuming the daytime rainfall to occur during a period of specified length. The versions 'instant rain' assume the rainfall to occur instantaneously at mid-day.

The values of parameters S, k and A were adjusted so that the interception sum for 1974 became equal to the measured sum i e 101 mm. Then it appears that also the sums for 1973 agree fairly well with the measured sums.

The correlation coefficient values at the bottom of table 2 are similar for the five model versions (about 0.985). In considering also the correlation to the data of total rainfall (which is smaller or 0.964) it is seen that the model makes better interception predictions than using the total rainfall data only.

The runs I - III of table 2 were made for S = 2 mm and k = 0.5 (or p = 0.5 for the free throughfall coefficient, p = 1-k) obtained in an earlier study of the same data, see Bringfelt and Hårsmar (1974). For the version "extended rain" (run No. III) A had to take the value 0.18 in order to get the sum 101 mm for 1974.

The above values of S and p (= 1-k) are rather high compared to other literature (see discussion of Bringfelt and Hårsmar, 1974). Therefore model runs IV and V were made. Then it turned out that the value A = 0.45 could be combined with lower S and p maintaining the sum 101 mm for 1974.

Run No. V is considered to be the most realistic, since the value of the free throughfall coefficient p = 0.367 (corresponding to k = 0.633) is probably better than p = 0.5 for the dense canopy. Furthermore, the sum of squares of differences between measured and calculated interception amounts is seen to be smallest (= 38.5) in this case. The parameter values and version of run No. V will be used in what follows.

In the model used above, no interception evaporation is assumed to occur during nighttime. However, Pearce et al. (1980) state that the energy used for interception evaporation is provided by large scale advection rather than radiation. Therefore, they say that nighttime evaporation rates from a wet forest canopy will not necessarily differ from daytime rates.

Model tests could have been made here, assuming also nighttime evaporation. However, this will be left for later studies using data from other forest sites as well. Then, the parameter values arrived at will be more safe and easier to compare to literature data. Using such a model probably will not improve the test results of the present study very much.

Rain collection period of troughs	Measured total rainfall (mm)	Evaporation of rain water intercepted on the forest canopy (mm): Measured	Calculated by version "instant rain": I	Calculated by version "instant rain": II	Calculated by version "extended rain": III	Calculated by version "extended rain": IV	Calculated by version "extended rain": V	Run No
			A • NET	A • ASTR • VCD	A • ASTR • VCD	A • ASTR • VCD	A • ASTR • VCD	form used for E_D
			2.0	2.0	2.0	1.7	1.5	S (mm)
			0.5	0.5	0.5	0.5	0.633	k
			0.0065	0.7	0.18	0.45	0.45	A $mm\,h^{-1}/(g\,m^{-3})$
			-	-	0.05	0.05	0.05	M mm/hr
			-	-	0.16	0.16	0.16	T_U mm
730517-0604	33.0	12.6	11.61	11.61	12.40	11.20	11.30	
0609-0613	7.0	2.8	2.56	2.56	2.62	2.32	2.26	
0625-0812	154.8	32.8	35.93	36.30	36.11	34.97	33.95	
0815-0904	28.0	7.4	6.47	6.47	6.62	6.02	6.16	
0904-0912	2.9	1.7	1.45	1.44	1.50	1.51	1.87	
0912-0915	0.8	0.5	0.40	0.40	0.40	0.40	0.51	
0919-1002	61.3	16.0	16.83	17.10	15.94	16.24	15.39	
SUM 1973	287.8	73.8	75.25	75.88	75.59	72.66	71.44	
740524-0611	33.2	14.2	15.81	15.73	15.84	15.47	16.00	
0617-0711	65.0	14.3	17.73	17.74	19.09	17.99	18.44	
0711-0730	54.1	14.5	11.47	11.46	12.21	11.63	11.96	
0730-0802	0.7	0.3	0.35	0.35	0.39	0.40	0.47	
0809-0820	62.7	14.1	12.17	12.19	13.28	12.78	13.05	
0826-0910	48.9	14.8	14.31	12.54	12.97	12.71	12.51	
0919-1010	100.0	28.8	29.13	30.99	27.03	29.73	28.82	
SUM 1974	364.6	101.0	100.97	101.00	100.81	100.71	101.25	
R	0.964	-	0.988	0.986	0.983	0.987	0.986	
$\sum_1^{14}(x_{CALC}-x_{MEAS})^2$			40.1	52.4	49.7	39.4	38.5	

Table 2

Results from five alternative versions of the interception model compared to measured data. The versions have been described in the text. For the meaning of the parameters - see the symbol list. At the bottom of the table are given values of R, the correlation coefficient and $\sum_1^{14} (x_{CALC} - x_{MEAS})^2$, the sum of squares of differences between the 14 values of the column concerned and the corresponding measured interception amounts.

Model for interception on low vegetation and ground

In equations 8 and 9 the amounts of throughfall that have reached the low vegetation and ground during the night and daytime rainfall respectively are calculated from the water balance of the canopy. The throughfall amounts are used in the simplified equation (10) for evaporation of water intercepted on the ground and low vegetation.

This submodel cannot be tested against the trough data since the troughs were sited at about 1.5 m above ground or above the level of low vegetation and ground structures. A crude test is possible only in connection with the test of the combined evapotranspiration model. There, the value 0.16 mm for the water storage capacity T_U will be derived.

4.3 Transpiration model

This model presupposes a completely dry forest canopy. Bringfelt (1982) has tested some expressions for the transpiration flux E and canopy surface conductance k_s as function of global radiation (RIS) and vapour concentration deficit (VCD) against measuring data from the Velen site in 1973 and 1974. Hourly transpiration flux values for 52 days were evaluated by the Bowen ratio-energy balance method, using net radiation and vertical profiles measured above the dry forest canopy.

Daily averages of the flux rates were determined of transpiration E and global radiation RIS and of the vapour concentration deficit VCD. The expression derived from Lohammar et al (1980) showed to give good fit to the data and led to equation (12) for the transpiration flux rate.

The data in 1973 (15 days) gave that

$a = 0.8645 \quad b = 0.0075 \quad c = 0.3226$

and the 1974 data (37 days)

$a = 0.986 \quad b = 0.0191 \quad c = 0.1942$

$\overline{VCD}$ daytime average vapour concentration deficit (g/m^3)

$\overline{RIS}$ and $\overline{E}$ are daytime average flux rates of global radiation and transpiration ($W\ m^{-2}$).

These expressions give that there is a systematic difference (≈30 %) in transpiration level for fixed $\overline{VCD}$ and $\overline{RIS}$ between the two summer seasons. This cannot reasonably be due to errors in measurement only and there are independent indications that the difference is real. Both alternatives will be used in the tests below.

As discussed by Bringfelt (1982), the reason for the smaller transpiration rates in 1974 than in 1973 may be the very dry spring of 1974 (only 2 mm precipitation between March 22 and May 26). This could have reduced the activity of the needles and leaves that summer, resulting in a smaller transpiration rate. However, there are no direct data available to confirm this hypothesis.

4.4 Combined evapotranspiration model

Description

This model consists of the following parts:

- evaporation of rain water intercepted on forest canopy (section 4.2);
- evaporation of rain water intercepted on low vegetation and ground (section 4.2);
- transpiration from the dry forest canopy (section 4.3);
- reduced transpiration in days with periods of wet canopy.

Interception

The evaporation of rain water intercepted on the forest canopy is calculated in days with rain during the daytime or during the previous night or days. As described in section 4.2 the model operates during successive days using the water stored on the canopy the previous sunset as input for each new night and day.

Transpiration

When the canopy is wet no transpiration is considered to take place. Calder and Newson (1979) have estimated that the number of hours when the canopy is wet is equal to 1.5 times the number of rain hours. Thus, in the model it was assumed that the daylength effective for transpiration is obtained by subtracting 50% of the duration of nighttime rainfall and 150% of the duration of daytime rainfall from the astronomical daylength.

In the model, the duration of nighttime (VN) and daytime rainfall (VR) are calculated by equation (13) and (1).

Then the transpiration flux rate $\overline{E}$ obtained by equation (12) will be multiplied by the 'daylength effective for transpiration':

MAX (0, ASTR - 0.5 VN - 1.5 VR)

to get the day's transpiration sum ETRA in eq (14).

This is used also for days with dry canopy (VN = VR = 0).

The duration of daytime rainfall (VR) was derived as a function of the amount of rainfall (AR), see figure 3. The function obtained was used for modelling also the duration of nighttime rainfall (equation 13). Figure 3 shows very large scatter. This can probably be reduced, if separate analyses are made for different types of rainfall (showers, light rain etc.) given in the synoptic observations. Divisions as regards time of year and geographic location may also be made. Different kinds of data may be used for a study like this, such as synoptic data, rainfall records and manual notes.

Such a study would be worthwhile in making the evapotranspiration model more general.

As will be seen in section 6, the crude relation used in the present transpiration model gives good agreement with monthly measured data but larger scatter for daily data.

The daily input and output data for the combined evapotranspiration model have been listed on computer prints. The final result, the total evapotranspiration E_{TOT} should be compared to the measured value E_{BOW}. This can be made for the two summer seasons in table 3.

The parameter values for the interception submodel have been adapted to the data of 1974 and showed good agreement also for 1973, see section 4.2.

The parameters (a, b, c) of the transpiration submodel were deduced for 1973 and 1974 separately using only days with completely dry canopy, see section 4.3.

Using also the parameter values (0.5 and 1.5) of Calder and Newson (1979) which give "daylength effective for transpiration" in partly rainy days, results in a good agreement with measured data for 1973 and 1974 separately, see table 3, underlined figures. This indicates that these parameter values are reasonable. See also section 6.1.

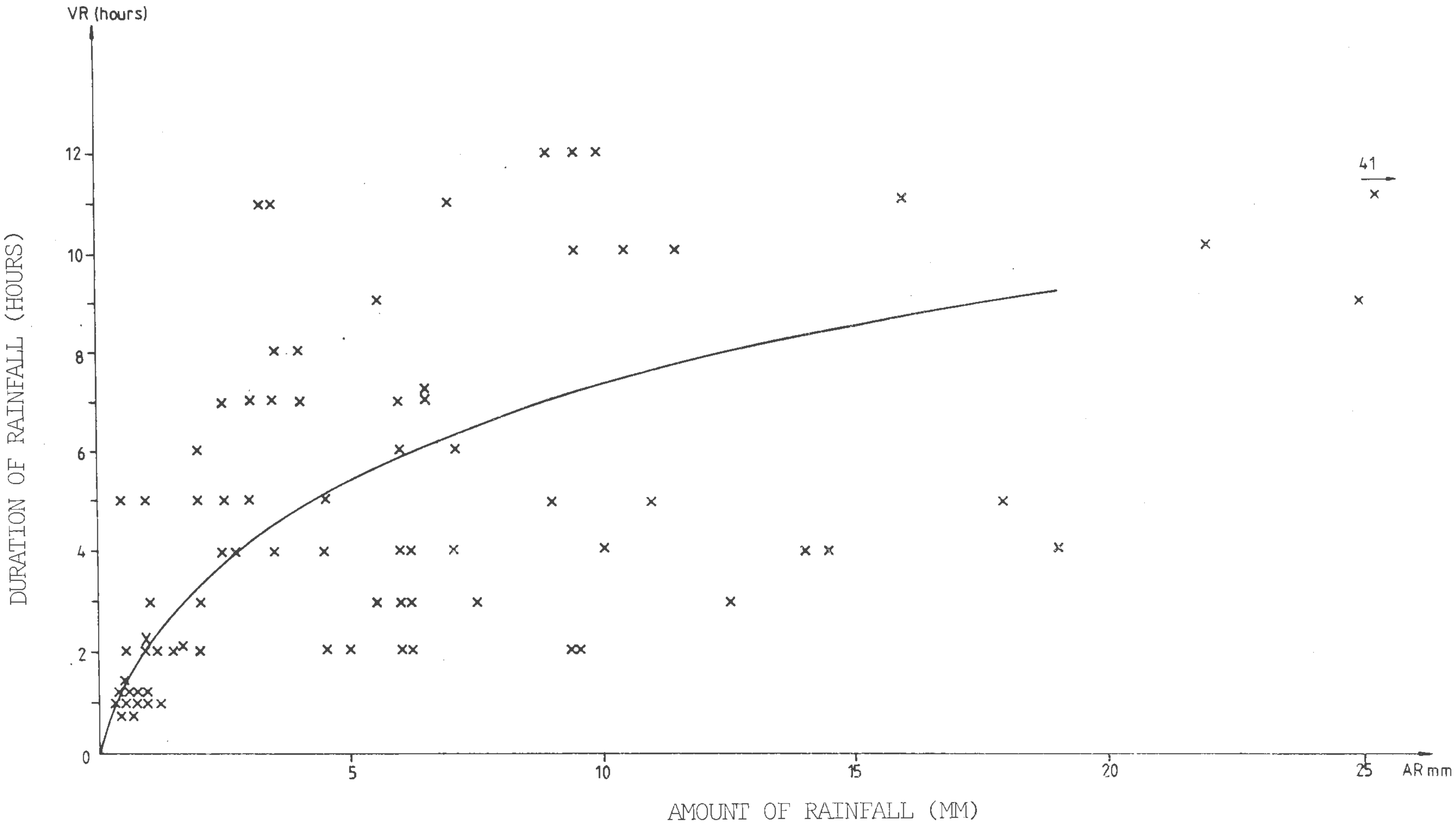


Figure 3 Deriving the relation for the furation VR as function of the amount AR for days with rainfall. Data from May - Oct. of 1972-74 at the Velen site have been used. Only daytime data (07 - 19 hours). The relation obtained was $VR = 7 \cdot {}^{10}\log(1 + AR)$, see the curve.

This simple way of reducing the "effective daylength" can be replaced by a physically more attractive approach using the exponential function for decay of stored water of the interception submodel.

Using parameter values for transpiration deduced from 1974 gives underestimate of the 1973 evapotranspiration by about 30% (108 mm vs 141 mm). An equally large overestimate is made using the 1973 values of a, b and c in calculating the 1974 evapotranspiration (271 mm vs 208 mm).

This is a result of the systematic difference in transpiration between the two summer seasons as discussed in section 4.3.

It is interesting to study the relative magnitude of the evaporation of intercepted rain water and the transpiration. Both these quantities have been adapted to the corresponding measured data using the results from the interception troughs and the meteorological mast respectively. Studying the sum of the two cases denoted by a) in table 3 it turns out that canopy interception (EIC) is 19% of total evapotranspiration (ETOT) while transpiration is about 78%. The rest 3% is evaporation of interception on low vegetation and ground (EIU).

The parameters of the two interception models have been adapted to get this order of magnitude of EIU. Since no direct data of EIU are available from the site some values given by Monteith (1975) have been used. There the work of Helvey and Patric (1965) was referred to giving that for a forest EIU is of the order of 2 - 5% of annual rainfall. In our data (see "all days" of table 3) EIU was adapted so that is became some 3.5% of total rainfall (10/288 for 1973 and 14/365 for 1974).

Table 3

Test of evapotranspiration model (combined model) using data from the forest site Velen. The following values for the parameters will be used in the tests presented below (see case V of table 2).

Interception submodel:

$S = 1.5$ mm

$k = 0.633$

$A = 0.45$ mm $h^{-1}/(g\ m^{-3})$

$M = 0.05$ mm/h

$T_U = 0.16$ mm

Transpiration submodel:

For values of a, b and c, see 4.3. Two sets of values will be used: one set deduced from data of 1973, the other set deduced from data of 1974.

The figures are sums in mm over the days specified.

AN rainfall during the previous night (19-07)

AR rainfall during the day (07-19)

EIC evaporation by interception model for forest canopy

EIU evaporation by interception model for low vegetation and ground

ETRA transpiration by model for forest canopy

ETOT = EIC + EIU + ETRA calculated total evapotranspiration

EBOW measured total evapotranspiration

Data of	Values of a,b,c deduced from transpiration data of	All days				Days with complete data				
		AN	AR	EIC	EIU	EIC	EIU	ETRA	ETOT	EBOW
a) 1973	1973	120	168	71	10	24	4	110	138	141
1973	1974	120	168	71	10	24	4	80	108	141
		(139 days)					(43 days)			
1974	1973	102	263	101	14	42	6	223	271	208
a) 1974	1974	102	263	101	14	42	6	161	210	208
		(157 days)					(84 days)			

If evapotranspiration is to be modelled on days with missing site data, or in other areas, it is necessary to use routine observations from neighbouring synoptic stations. This problem will be studied in the rest of this report.

5. USE OF SYNOPTIC DATA AS INPUT TO COMBINED EVAPOTRANSPIRATION MODEL

If routine observations from synoptic stations can be used, it will be possible to calculate forest evapotranspiration almost continuously since synoptic data are available for almost every day. Furthermore, a resolution between different areas will be possible, since in Sweden there are about 190 synoptic stations. Here will be treated only the seven stations surrounding the Velen area.

5.1 Synoptic stations used

Routine observations from seven synoptic stations have been used to calculate daily evapotranspiration for the years 1967 - 1974. The stations are located around the Velen site at distances from 20 km to 65 km. Their positions can be seen on the map of figure 4 and latitudes-longitudes in table 4. This table also shows the number of synoptic observations per day during the various years.

Description of the siting of the stations:

Åtorp Immediately to the west of the station there is spruce forest. To the east there is agricultural land. The station is in a garden.

Västerplana is located in an agricultural area 1.5 km to the east of Lake Vänern.

Borgunda is located in agricultural terrain sloping eastward.

Snavlunda is located in rolling agricultural country alternating with groves and lakes.

Fägre. The station is located in a garden in a flat agricultural area. Immediately to the east there is a grove at a height 35 m above the station level. Good wind shelter for the rain gauge is given from trees and buildings.

Karlsborg is located on the western shore of Lake Vättern.

Mariedamm is located in forest terrain sloping eastward.

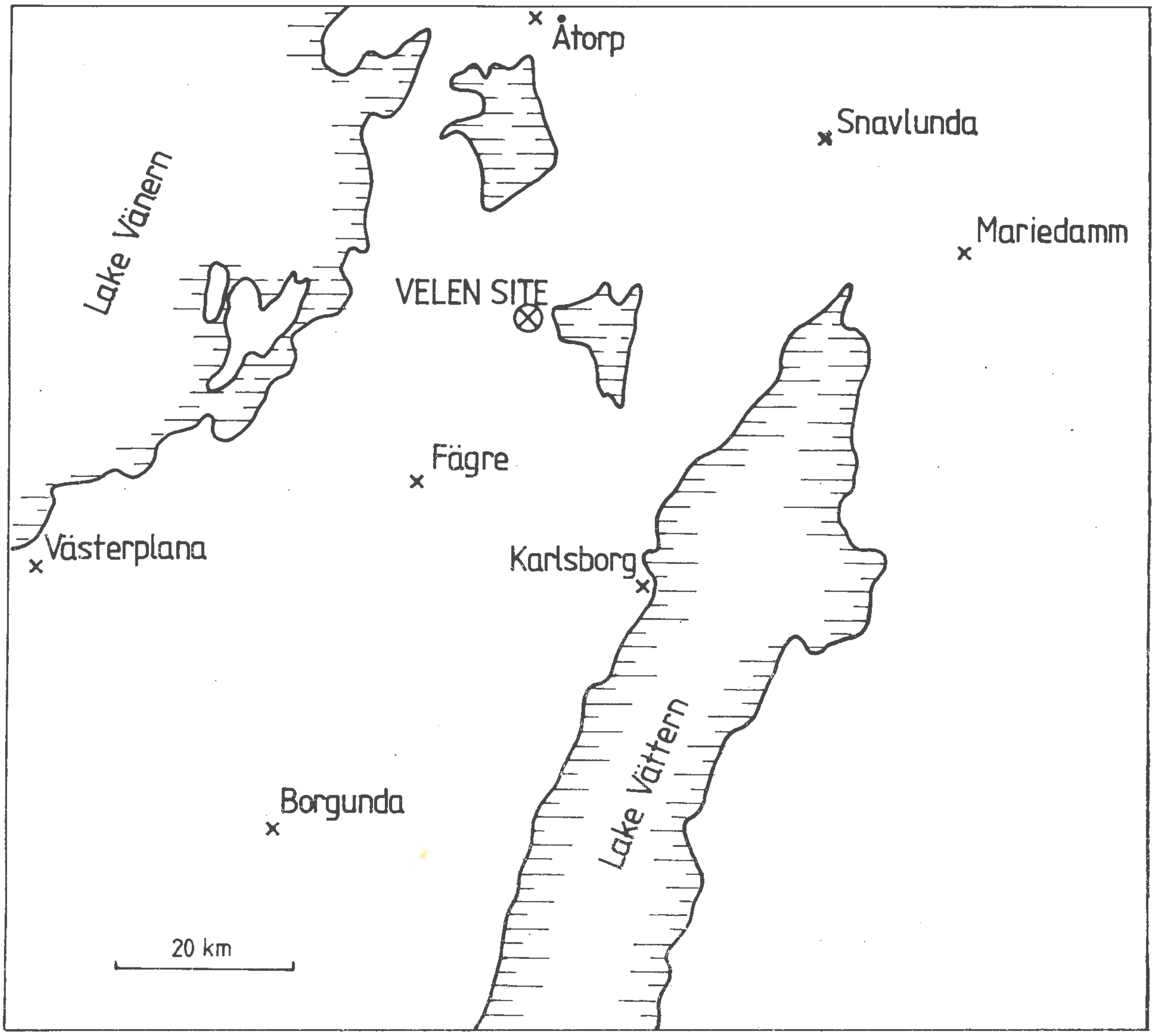


Figure 4 The map shows the location of the Velen site (between Lakes Vänern and Vättern).

Daily routine observations from the seven synoptic stations shown have been used in the forest evapotranspiration model.

Table 4 Number of daily synoptic observations at the seven stations used

Synop-stat no	Latitude	Longitude	Name	YEAR 67	68	69	70	71	72	73	74
428	59°5'50"	14°22'5"	Åtorp	3	3	3	3	3	3	6	6
532	58°34'	13°21'	Västerplana	3	3	3	3	3	3	6	6
534	58°17'	13°48'	Borgunda	-	-	-	-	3	3	6	6
541	58°57'50"	14°54"0"	Snavlunda	4	4	4	4	4	4	8	8
543	58°39'	14°8'	Fägre	3	3	3	3	3	3	6	6
544	58°31'	14°32'	Karlsborg	4	4	4	4	4	4	8	8
560	58°52'	15°9'	Mariedamm	3	3	3	3	3	3	6	6

3 means obs at 7, 13, 19h (06, 12, 18 GMT)

6 means obs at 4, 7, 10, 13, 16, 19h

Only these two sets of observations have been in this study. 4 (8) in the table means that the above 3 (6) observations are available and have been used.

5.2 Synoptic data used

The most important daily meteorological input to the model described in section 4 are

- rainfall during the 12 preceding night-time hours and rainfall during the 12 day-time hours;
- day-time average of water vapour concentration deficit;
- day-time average global radiation flux.

For more details see section 4.1 and the appendix.

This section will describe how synoptic data are used to calculate these meteorological data necessary as input to the evapotranspiration model.

Calculation of 12 hourly rainfall

The synoptic data contain rainfall measured at 07h and 19h. A rain-free 12h-period is marked by -1 and a small but not measureable amount by 0. As input to the model these two cases have been given as zero preicpitation. Measured amounts were increased by 10 % in order to correct for the various kinds of losses at the gauge (evaporation loss, aerodynamic wind speed loss, e.g.). See Eriksson (1980).

In table 5 the monthly rainfall amounts measured at the synoptic stations are compared with the amounts collected by the troughs in clearings at the Velen site. The interception amounts calculated by the model will be directly related to the rainfall amounts. Thus, if the rainfall is too small (as can be suspected using synoptic rainfall data, see below) the interception predicted will also be too small.

The amounts of Karlsborg are relatively small, and this is due to the free exposure of the gauge (section 5.1), so this station plus Mariedamm (having incomplete data) have been excluded in the comparison made in table 5.

The rainfall sums from the five remaining synoptic stations (increased by 10 %) are, in the average, smaller than the amounts collected by the troughs at the Velen forest site. Thus, a correction of 30 % instead of 10 % to the 454 mm would correspond to the sum (589 mm) of the Velen site. One reason for the large difference is that rainfall over forests are often larger than over other surfaces. Furthermore, also some of the five remaining stations are probably rather freely exposed.

Table 5 *Monthly rainfall (mm) measured at seven synoptic stations and in clearings at the Velen site by troughs.*

	MONTH	Åtorp	Västerplana	Borgunda	Snavlunda	Fägre	Karlsborg	Mariedamm	Average over the five stations to the left	Increased by 10 %	Velen site (troughs)
1973	06	29	13	17	16	19	13	20	19	21	20
	07	93	76	64	120	49	40	69	80	88	100
	08	52	57	48	49	46	22	47	50	55	76
	09	60	58	90	51	64	66	72	65	72	67
1974	05	16	21	32	23	19	17	-	22	24	18
	06	42	21	53	46	60	26	54	44	48	67
	07	64	37	43	45	40	40	77	46	51	68
	08	76	32	47	29	39	7	50	45	50	74
	09	111	77	54	97	74	47	-	83	91	99
Sums		543	392	448	476	410	278		454	499	589
Sums increased by 10 %		597	431	493	524	451	306		499		

Thus, larger corrections than 10 % would have been justified for most stations before running the forest model. However, more work is needed to establish proper correction factors. As illustrated by the similar model results in table 9 for Karlsborg and Åtorp 1973-74, the model results are rather insensitive to given rainfall amounts. More rain will give more evaporation of intercepted rain but smaller transpiration.

Calculation of daytime average water vapour concentration deficit ($\overline{VCD}$)

A. Synoptic data available at six observations a day. The observations at 4, 7, 10, 13, 16, 19h (3, 6, 9, 12, 15, 18 GMT) are used.

Each observation consists of a value of relative humidity R_h (%), water vapour pressure e (mb) and temperature T (^oC).

Then VCD is calculated from

$$VCD = e(\frac{100}{R_h} - 1) \cdot \frac{0.622/R_d}{273.16+T} \ (g\ m^{-3})$$

where R_d = $2.87 \cdot 10^{-3}$ mb g^{-1} $K^{-1} m^3$ is the gas constant of air. The daytime $\overline{VCD}$-value is formed by averaging the VCD-values from the observations during the astronomical day (sun above horizon).

In the upper part of figure 5 these $\overline{VCD}$-values calculated with six daily synoptic observations available at Fägre are compared to daytime averages measured in the Velen forest.

B. Synoptic data available as three observations a day.

Used are observations at 7, 13, 19h (6, 12, 18 GMT).

VCD is calculated as above for 7, 13, 19h giving values y_7, y_{13}, y_{19}.

Taking the time of day as x-axis and VCD as y-axis, the daytime average of VCD is calculated from the mean ordinate of the parabola passing through (x= 7, y = y_7), (x = 13, y = y_{13}), (x = 19, y = y_{19}):

$$y = \frac{y_7-2y_{13}+y_{19}}{72} \ x^2 + \frac{1}{18} \ (-8y_7+13y_{13}- 5y_{19})x + \frac{1}{72} \ (247y_7-266y_{13}+91y_{19})$$

Then, average of VCD over the astronomical day (sunrise at x_1, sunset at x_2)

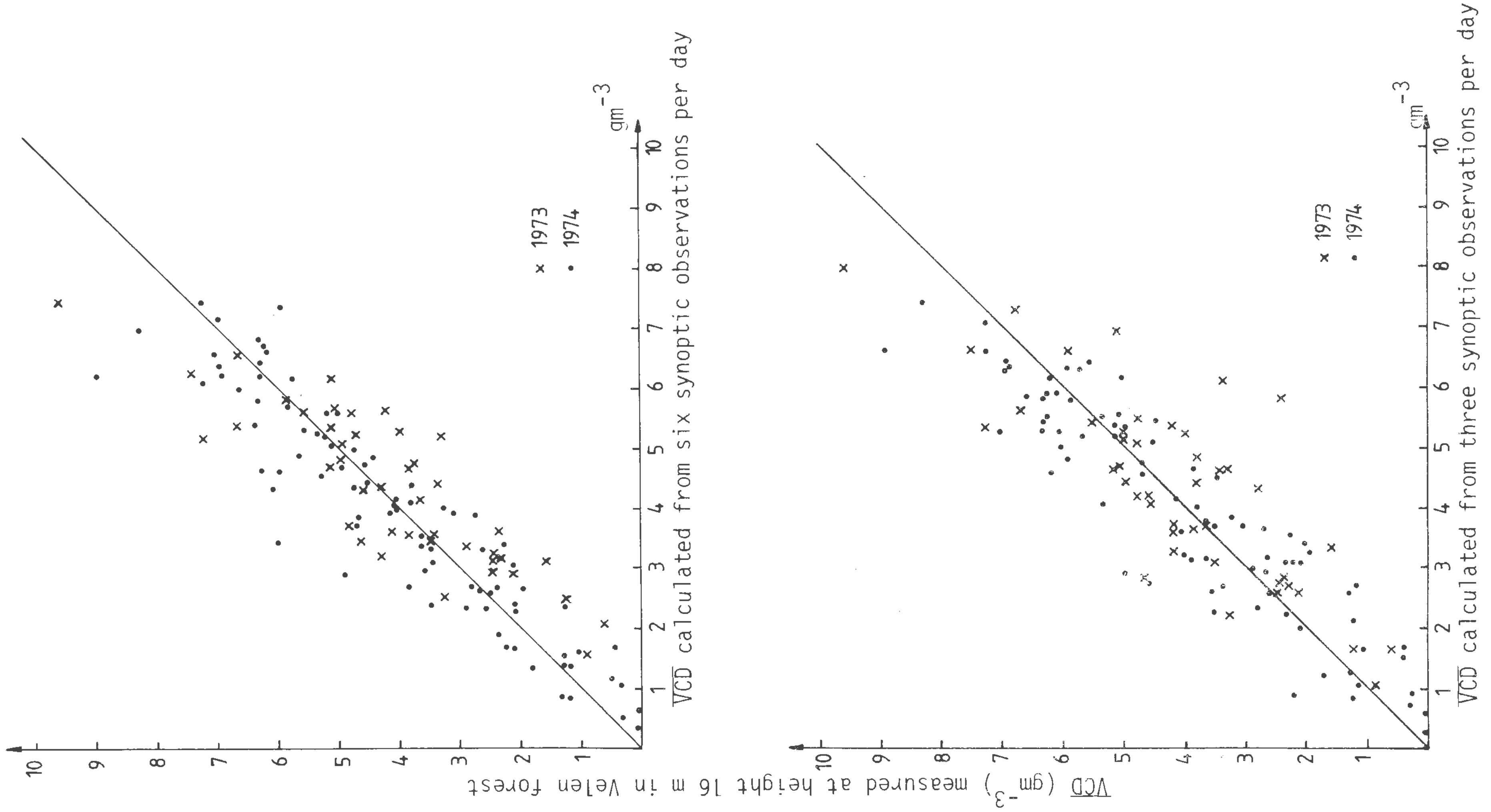


Figure 5 Daytime averages of water vapour concentration deficit in the air (g m^{-3}). Comparison between measurements at the forest site in Velen and values calculated from synoptic observations made at Fägre 20 km away. In the diagrams have been used six and three synoptic observations per day respectively. The same days have been studied in both cases.

is calculated as $\frac{1}{x_2-x_1} \int_{x_1}^{x_2} y \, dx$. Since VCD cannot be negative, y is taken as 0 wherever $y < 0$ in the integration interval $x_1 - x_2$.

In the lower part of figure 5 these VCD-values are compared to the measured daytime averages. As expected the figure shows that the scatter of values is larger using only three observations a day. The comparison has been made for the same days in both cases.

Using three observations a day (which is more often available than six observations a day, see table 4) the scatter in figure 5 shows that the standard deviation of the error is about 20 % of the computed daily VCD-value.

Figure 5 shows that there is no systematic difference between the VCD-values measured in the Velen forest canopy (at height 16 m) and the values obtained from synoptic data at Fägre 20 km away. As stated above, this station is only partly in forest surroundings. This confirms what was believed, namely that daytime vapour concentration deficit shows no systematic difference between forest and agricultural sites.

Calculation of daytime average global radiation flux, $\overline{RIS}$

These calculations have been made by a computerized radiation model, kindly supplied by Roger Taesler.

The global radiation to a horizontal surface on the ground is calculated for each hour during the astronomical day and then averaged to form $\overline{RIS}$.

For each hour the model uses
- the sun elevation calculated from latitude and time (degrees)
- water vapour pressure (mb)
- total cloud cover (eights)
- the albedo of cloud and ground.

At first the global radiation with clear skies is calculated. Then the optical airmass is calculated from the sun elevation. The attenuation of solar radiation for 62 wavelengths of a decomposition of the solar spectrum is calculated using the optical airmass, the water vapour pressure and the turbidity.

Following Liljequist (1979) the effect of cloudiness is considered by reducing the global radiation with clear skies by a factor composed of albedoes:

$$\frac{1 - a_{CLC}}{1 - a_{GROUND} \cdot a_{CLC}}$$

where the denominator regards repeated light reflexions at cloud base and ground.

a_{GROUND} is the albedo of the forest. It is known that forest albedoes are low, see Stewart (1971), and here will be used $a_{GROUND} = 0.08$ the value obtained from measurements above the Velen forest. see Bringfelt et al (1977).

For the effective albedo of the sky is used

$$a_{CLC} = \frac{n}{8} \cdot a_{CL}$$

where n is total cloud cover in eights and a_{CL} is the effective albedo of the cloud cover as such.

Calculations have been made using various forms for a_{CL}. The following expression showed the best fit to the measured global radiation values over the Velen forest:

$$a_{CL} = 0.033 \cdot n + 0.434$$

giving $a_{CL} = 0.5$ for $n = 2$ and
$a_{CL} = 0.7$ for $n = 8$

This expresses that clouds covering only a small part of the sky will have reduced influence on the sky albedo a_{CLC}. On a long term average a relation of this kind seems plausible.

Global radiation is calculated for each daylight hour and in the same way for the two cases of six or three daily synoptic observations available. Table 6 shows, for a given hour, what observation of cloudiness and humidity is used.

Figure 6 compares the ability of the model to simulate daily global radiation sums for the two cases of six and three daily synoptic observations. Exactly the same days have been used in both cases. The improvement in using six observations is noticeable but not as clear as for VCD in figure 5.

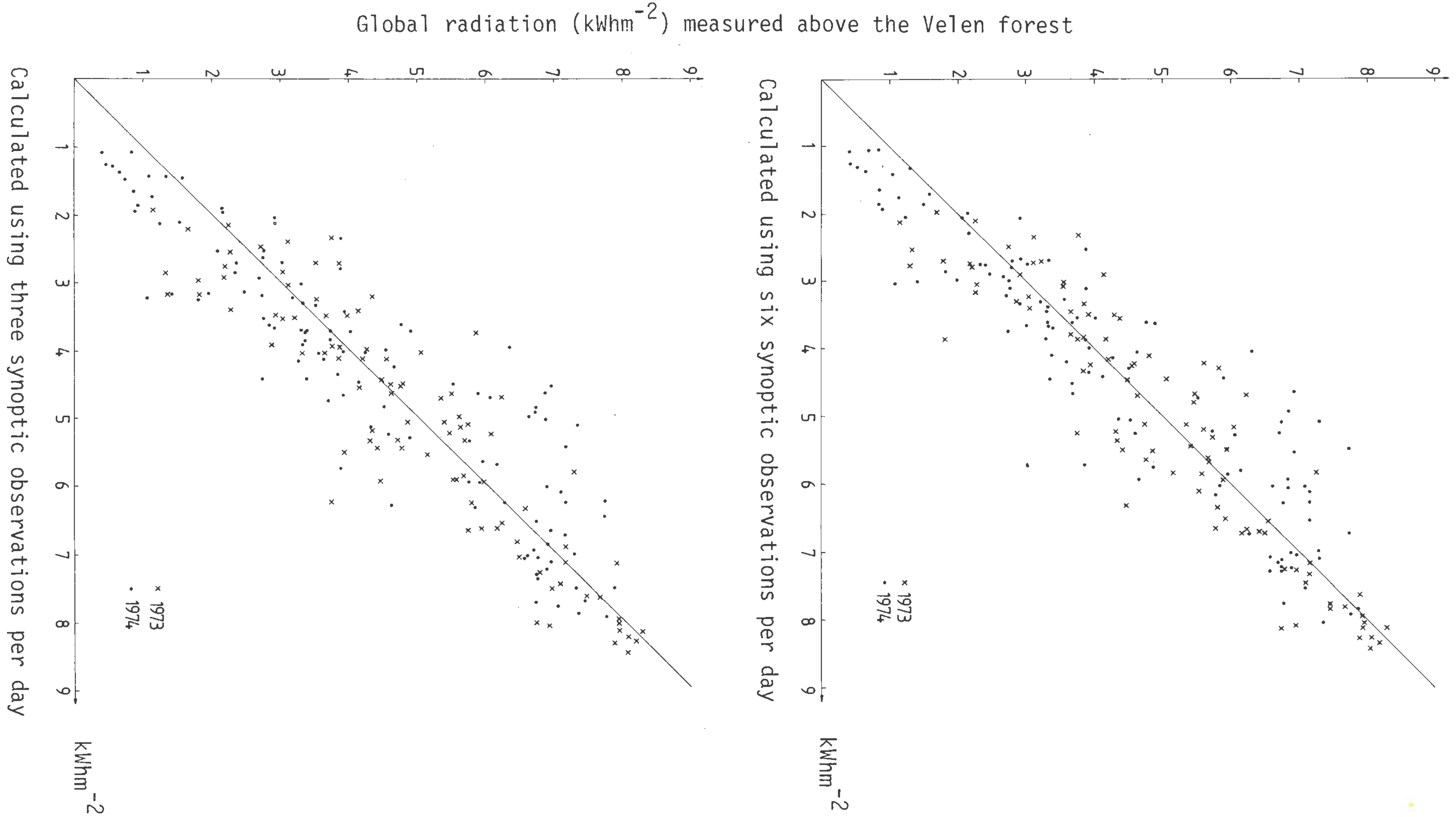


Figure 6 Daily sums of global radiation over forest (kWh m^{-2}). Comparison between measurements above the forest in Velen and values calculated by the radiation model (parameter values described in the text) using synoptic observations made at Fägre 20 km away. In the diagrams have been used six and three synoptic observations per day respectively. The same days have been studied in both cases.

The standard deviation of the error is about 20 % of the computed radiation sum, i.e. of the same magnitude as for VCD.

Table 6 *The figures give the hour of the synoptic observation used to calculate global radiation for each daylight hour.*
Thus, for hour 9 the observation made at 10h (7h) is used if six (three) daily observations are available.

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Six daily obs. available	4	4	4	4	4	7	7	7	10	10	10	13	13	13	16	16	16	19	19	19	19	19	19	19
Three daily obs. available	7	7	7	7	7	7	7	7	7	13	13	13	13	13	13	19	19	19	19	19	19	19	19	19

5.3 Data processing

The synoptic data have once been stored routinely on magnetic tapes. One such tape contains the data from all 190 stations in Sweden during one year. In order to improve the ease of access, the data of 1967 - 1974 at the seven stations used in this study were converted to one single tape, which can be read by the forest evapotranspiration model, which is a FORTRAN program.

The data on this new tape have been stored on a monthly basis in the following order and for one day the data are arranged according to table 7.

January 1967: Station 428, 532, 534, 541, 543, 544, 560.
February 1967: Station 428, 532, 534, 541, 543, 544, 560.
. . .
December 1974: Station 428, 532, 534, 541, 543, 544, 560.

These data are read on a daily basis by the model program. The prescribed parameter values are used, and the results are given as daily values of evapotranspiration.

Table 7 *Storage of one day's synoptic data on a tape prepared for the evapotranspiration model. The figures give order number of value described.*

Synop station no	Climate station no	Latitude	Longitude	Height above sea level	River area no	Year of start of observations	Year	Month	Date
1	2	3	4	5	6	7	8	9	10

Observation hour	Total cloudiness	Wind direction	Wind speed	Relative humidity	Vapour pressure	Temperature	Visibility	Weather	Past weather	Cloudiness (height h)	Type of low cloud	Type of medium cloud	Type of high cloud	Height h
01	11	12	13	14	15	16	17	18	19	20	21	22	23	24
04	25	26	27	28	29	30	31	32	33	34	35	36	37	38
07	39	40	41	42	43	44	45	46	47	48	49	50	51	52
10	53	54	55	56	57	58	59	60	61	62	63	64	65	66
13	67	68	69	70	71	72	73	74	75	76	77	78	79	80
16	81	82	83	84	85	86	87	88	89	90	91	92	93	94
19	95	96	97	98	99	100	101	102	103	104	105	106	107	108
22	109	110	111	112	113	114	115	116	117	118	119	120	121	122

Maximum temperature	Minimum temperature	Precipitation 19-07 hours	Precipitation 07-19 hours	Snow depth	Snow cover	Station name	Precipitation type 19-07 hours	Precipitation type 07-19 hours
123	124	125	126	127	128	TEXT	TEXT	TEXT

Below is given an example of the model output for one month of daily data. The data to the left in the heading of the table are values used by the model (calculated from synoptic data):

AN	rainfall during the previous night (19 - 07h) mm
AR	" " " day (07 - 19) mm
ASTR	astronomical daylength calculated from latitude and time of year (h)
GLOBAL	global radiation Wh m^{-2}
RIS	daytime mean global radiation flux (W m^{-2})
VCD	daytime mean vapour concentration deficit (g/m^3)

Parameter values: See head of data list.

The values calculated by the model are given to the right in the heading (mm):

EIC	evaporation by interception model for forest canopy
EIU	evaporation by interception model for low vegetation and ground
ETRA	transpiration by model for forest canopy
ETOT	= EIC + EIU + ETRA calculated total evapotranspiration

```
ÉXQT B9-PRG.EVASYN
F O R E S T   E V A P O T R A N S P I R A T I O N   M O D E L   U S I N G   S Y N O P T I C   D A T A

TREE CANOPY INTERCEPTION MODEL,PARAMETERS:
PC=FREE THROUGHFALL COEFF,KC=1-PC=  .63300000
SC=WATER STORAGE CAPACITY(MM)=  1.5000000      AC=COEFF FOR RATE OF INTERCEPTION EVAPORATION=  .45000000

GROUND AND LOW VEGETATION INTERCEPTION MODEL, PARAMETER TU=  .16000000

TREE CANOPY TRANSPIRATION MODEL,PARAMETERS:
A=  .93600000     B=  .19100000-001 C=  .19420000

DAILY DATA:
AN=RAINFALL 19-07, AR=RAINFALL07-19(MM)
GLOBAL=DAYTIME GLOBAL RADIATION WH/M2,                    RIS =DAYTIME MEAN GLOBAL RADIATION FLUX (W/M2)
VCD=DAYTIME MEAN VAPOUR CONCENTRATION DEFICIT(G/M3),      ASTR=ASTRONOMICAL DAYLENGTH(HOURS)

IN MM/DAY:
EIC(EIU)=EVAPORATION CALCULATED BY INTERCEPTION MODEL OF TREE CANOPY(UNDERCANOPY)
ETRA=CALCULATED TRANSPIRATION    ETOT=EIC+EIU+ETRA=CALCULATED TOTAL EVAPOTRANSPIRATION
```

DATE	AN	AR	ASTR	GLOBAL	RIS	VCD*ASTR	VCD	EIC	EIU	ETRA	ETOT
FÅGRE			SYNOPNR=		543	LATITUD=		5839			
19730801	.00	.00	16.39	4453	271.74	71.42	4.36	.00	.00	2.41	2.41
19730802	.00	.00	16.31	5366	359.59	94.85	5.81	.00	.00	2.89	2.89
19730803	.00	.33	16.24	6322	389.34	106.30	6.55	.22	.11	2.82	3.15
19730804	.11	11.22	16.16	2891	178.88	51.19	3.17	1.95	.20	.52	2.67
19730805	1.32	.44	16.09	2794	173.66	24.87	1.55	1.13	.30	.89	2.32
19730806	.00	.77	16.01	3391	211.78	72.60	4.53	.53	.16	1.93	2.61
19730807	7.81	.00	15.93	5817	365.09	89.36	5.61	1.50	.16	2.20	3.86
19730808	6.05	6.27	15.86	2777	175.16	32.81	2.07	3.28	.32	.32	3.92
19730809	.00	.00	15.78	6511	412.67	90.38	5.73	.01	.00	2.82	2.83
19730810	4.29	.66	15.70	2534	161.44	38.88	2.48	1.94	.32	1.02	3.28
19730811	.22	.00	15.62	5162	330.53	81.45	5.22	.14	.08	2.55	2.77
19730812	.00	.00	15.54	4467	287.47	86.38	5.56	.00	.00	2.61	2.61
19730813	.00	.00	15.46	6603	427.21	114.72	7.42	.00	.00	3.11	3.11
19730814	.00	.00	15.38	6652	432.66	142.10	9.24	.00	.00	3.37	3.37
19730815	.00	.00	15.29	6699	438.03	160.43	10.49	.00	.00	3.51	3.51
19730816	.00	.00	15.21	6496	427.08	131.45	8.64	.00	.00	3.25	3.25
19730817	.00	.00	15.13	6092	402.69	169.48	11.20	.00	.00	3.51	3.51
19730818	3.74	.00	15.05	5646	375.23	64.76	4.30	1.50	.16	1.94	3.60
19730819	.00	.00	14.96	4215	281.73	75.37	5.04	.00	.00	2.39	2.39
19730820	.00	.00	14.88	5169	347.44	72.32	4.86	.00	.00	2.40	2.40
19730821	2.20	.00	14.79	5606	378.93	62.93	4.25	1.39	.16	1.98	3.53
19730822	.00	.00	14.71	4291	291.71	67.58	4.59	.00	.00	2.25	2.25
19730823	.00	.00	14.62	4673	319.50	68.61	4.69	.00	.00	2.29	2.29
19730824	.00	.00	14.54	5593	384.66	80.70	5.55	.00	.00	2.54	2.54
19730825	.00	.00	14.45	5922	409.74	66.98	4.63	.00	.00	2.32	2.32
19730826	.00	.00	14.37	4774	332.28	81.07	5.64	.00	.00	2.43	2.43
19730827	.00	.00	14.28	3855	269.89	70.63	4.95	.00	.00	2.24	2.24
19730828	.00	.00	14.20	5355	377.20	106.08	7.47	.00	.00	2.83	2.83
19730829	.00	.00	14.11	3155	223.59	42.21	2.99	.00	.00	1.61	1.61
19730830	.00	.44	14.02	2327	165.93	54.27	3.87	.30	.14	1.54	1.98
19730831	3.63	.22	13.94	2694	193.29	44.07	3.16	1.65	.23	1.23	3.11
MONTHLY SUMS:											
197308	29.37	20.35	471.01	148802	9796.16	2516.25	165.63	15.55	2.34	69.79	87.68

6. TEST OF COMBINED MODEL USING INPUT OF SYNOPTIC DATA

In section 4.4 was described how the interception and transpiration submodels were combined to a forest evapotranspiration model. That model was calibrated and tested using data from the Velen site.

In section 5 was described how routine synoptic observations were used to form the input necessary for the combined evapotranspiration model.

All these operations have been included in one computer programme using synoptic data to directly calculate forest evapotranspiration. Example of the output from this final model was given in section 5.3.

In the earlier sections data taken at the Velen site were used to improve the models (e g by adapting values of the model parameters) before they were tested against remaining independent data from the site.

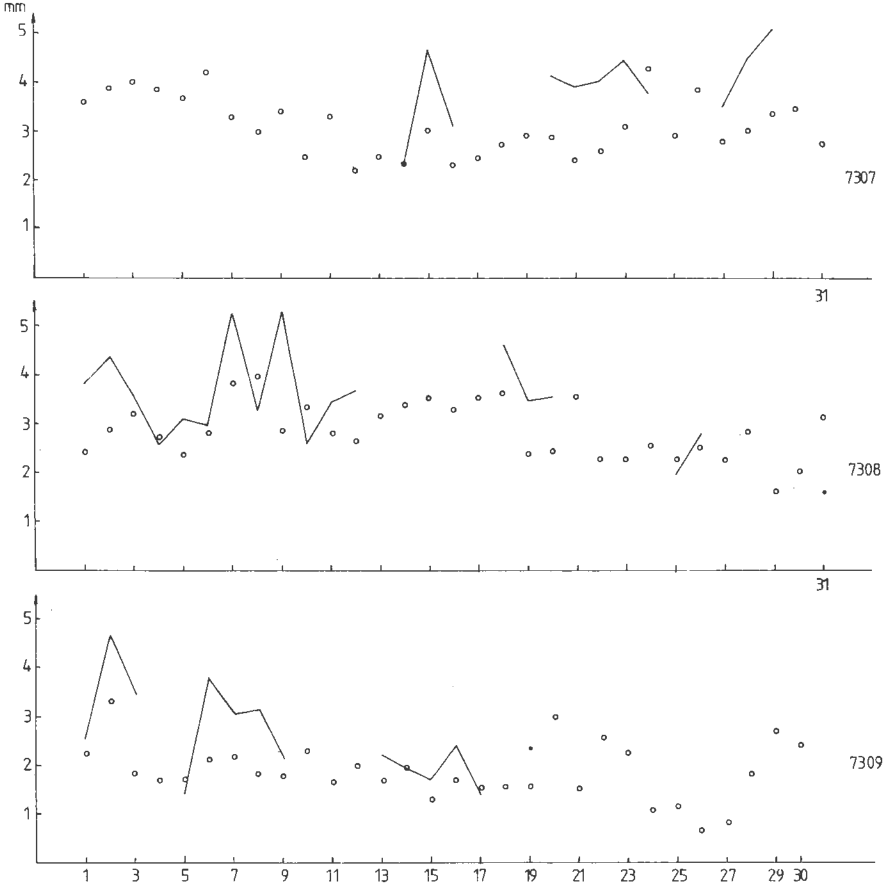
In this section using synoptic data as input no model improvement will be made but only a test and comparison with measured evapotranspiration data. In section 6.1 the model output will be compared to measured evapotranspiration data at the Velen site. In section 6.2.1 comparison will be made with the completely independent monthly evapotranspiration data obtained by the water balance method in the Velen basin during 1967-74. In section 6.2.2 comparisons will be made with estimates by the Penman formula.

6.1 Test against data of 1973 and 1974 from the Velen site

This test will be made on the same period as in section 4.4 but the input will be synoptic data instead of data from the Velen site.

Table 8 shows that the use of input synoptic data from Fägre (bottom of table) does not influence the evapotranspiration level compared to using input data from the Velen site itself (middle of table).

This shows that the input data of Fägre (daytime averages of vapour concentration deficit, global radiation flux and 12 hourly rainfall sums obtained from synoptic observations) are consistent with the Velen site input data as regards the computed evapotranspiration sum over several days. That the input data as such are also similar was shown in figures 5 and 6 where the calculated values using synoptic data from Fägre were plotted on a day-to-day basis together with the measured data at the Velen site.



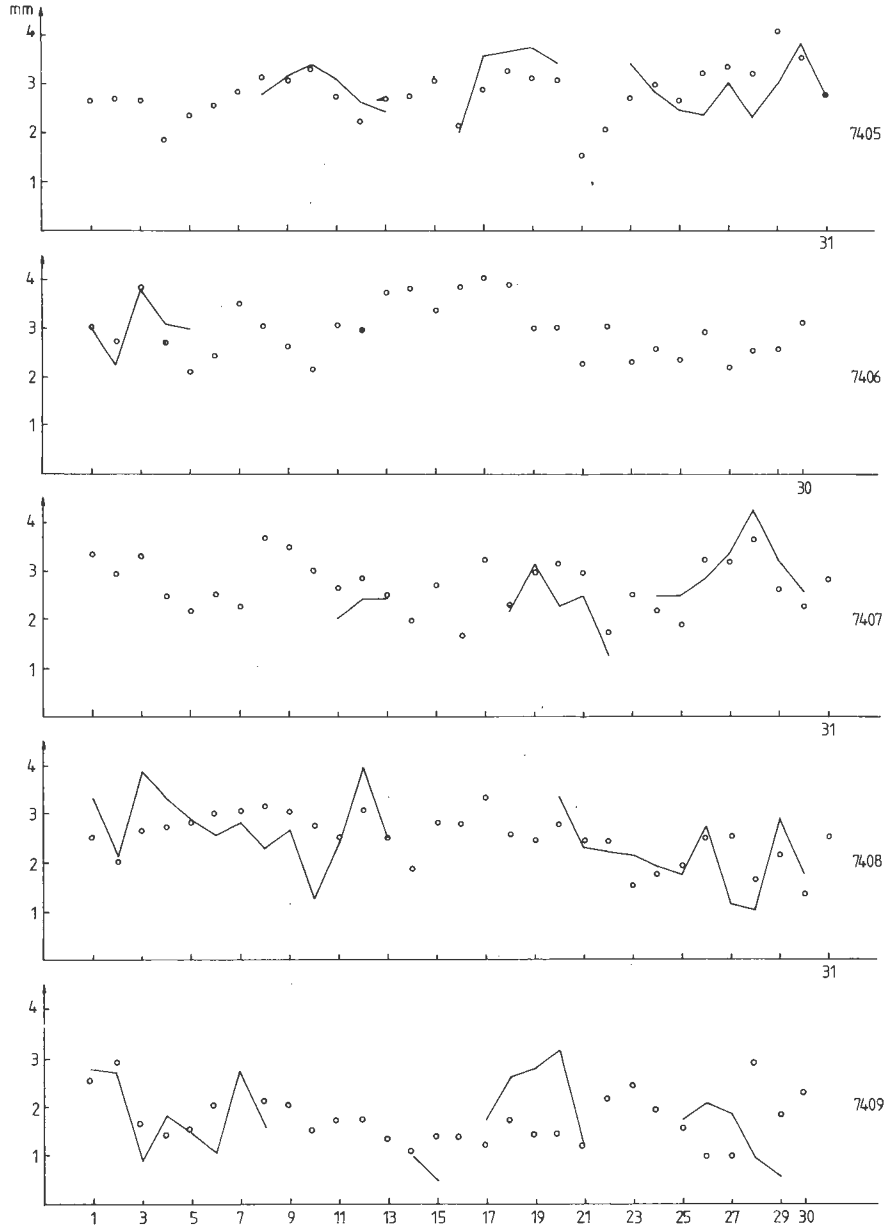


Figure 7

Comparison of daily values of forest evapotranspiration (mm) during 1973 and 1974.

The full lines give values evaluated from measurements at the Velen site by the Bowen ratio-energy balance method.

The circles give values computed by the model using routine observations from the nearest synoptic station Fägre 20 km from the Velen site. The values used of the constants in the transpiration submodel are all through those derived from the Velen measurements of 1974. The constants of the interception submodel are given in table 3.

For 1974 the model values in table 8 agree with the measured data since the model was adapted to these data. For 1973 the values generated by the same model are smaller than the measured values due to reasons discussed in section 4.4.

Figure 7 shows the same comparison but of values plotted on a day-to-day basis. Here the disagreement for individual days may be large. One reason is the scatter in daily VCD and global radiation values used as model input, see figures 5 and 6.

Another reason is the difficulty in determining the duration of daily rainfall (see figure 3) leading to an uncertain transpiration value. For the sums over months (or longer) these errors have been partly cancelled.

Table 8 *Sum of daily evapotranspiration data (mm) of 1973 and 1974 using values of model parameters adapted to the measurements of 1974.*

	1973	1974
Number of days	43	84
Measured at Velen site by Bowen ratio-energy balance method	141	208
Calculated by model using input data from the Velen site	108	210
Calculated by model using input data from the synoptic station Fägre	110	208

6.2 Test against monthly evapotranspiration estimates

In this section the forest model will use synoptic data to calculate monthly evapotranspiration sums for April - October of 1967 - 1974. The results are presented in table 9 for each of seven synoptic stations surrounding the Velen area. These values will now be compared to monthly estimates (table 9), made by the water balance method and the Penman formula.

6.2.1 Independent estimates by the water balance method

Table 9 shows independent monthly evapotranspiration estimates obtained by the water balance method using hydrological measurements in the Velen basin and the Nolsjön sub-basin. The Velen basin is about 18 km long in the N-S direction and at most 4 km in the E-W direction. It has only one outlet (in the south) where the total runoff was measured. The area is covered by forest to 66 %, lakes to 10 %, swamps to 12 %, and cultivated area.

The basins and the data have been described by Waldenström (1977). The water balance method and errors will be discussed later in this section.

In table 9 the forest model gives rather similar estimates for all synoptic stations. Figures 8, 9 and 11b compare graphically the estimates from three of the synoptic stations with the water balance results from the Velen basin. In figure 13 is presented on a time axis the same data as in 11b.

As can be seen, the agreement with the water balance estimates is very good for June, July and August. Such a good overall fit was scarcely expected since the transpiration values of 1974 (the summer from where the constants in the transpiration formula was taken) were found to be lower than for 1973 by about 30 per cent (for corresponding values of vapour concentration deficit and global radiation), see Bringfelt (1982).

In principle there is reason to believe the model adaption to 1974 to give good agreement with the water balance results for that year. As discussed by Bringfelt (1982) and section 4.3, the dry spring of that year could have given comparatively low stomatal activity the rest of the summer and therefore low values of evapotranspiration. Some tendency of this can be seen in figure 11b where the values for 1974 estimated by the water balance method (encircled ordinates for May, June, July and August) are often lower than for these months of the remaining years.

In principle the 1974 points for the summer months should be expected to lie on the 45°-line (with slope 1:1) and the remaining years should have larger ordinates. But the figure 11b shows lower ordinates throughout.

Possible reasons for these and other differences between the results of the model and the water balance method will be discussed below.

- The Velen basin is covered by forest to only 66%. This should reduce the interception loss so that the water balance method will appear to give smaller evaporation (as far as interception is concerned). However, there are also water losses from non-forested areas and little can be said of the total effect. As an illustration can be seen that the total water balance estimate summed over the relevant months of table 9 are quite similar for the Velen basin (2379 mm with 66% forest) and the Nolsjön subbasin (2406 mm with 84% forest). Therefore this effect has not been considered in the present forest evapotranspiration model.

		A								B		C	
Year	Month	Åtorp	Västerplana	Borgunda	Snavlunda	Fägre	Karlsborg	Mariedamm	Average over six synoptic stations (excl Borgunda)	Velen basin	Nolsjö subbasin	From synoptic data at Fägre	From detailed measurements in the Velen area
1967	09	62	55	–	52	52	41	55	53	50	–	40	–
	10	60	57	–	48	58	43	54	53	23	–	19	–
1968	04	66	56	–	65	64	51	64	61	13	–	54	40
	05	83	69	–	77	76	62	72	73	63	–	81	53
	06	111	100	–	107	102	96	101	103	93	–	133	97
	07	100	87	–	95	–	91	96	94	96	–	–	83
	08	94	84	–	88	81	77	83	85	83	–	89	47
	09	60	54	–	57	51	48	56	54	47	38	43	26
	10	47	42	–	45	39	36	42	42	74	39	12	1
1969	04	58	49	–	56	52	46	58	53	104	–	43	17
	05	80	71	–	76	80	69	74	75	44	41	79	56
	06	103	84	–	99	101	85	98	95	86	92	143	96
	07	97	76	–	98	94	79	94	90	79	73	129	102
	08	92	78	–	93	93	79	92	88	98	107	102	65
	09	56	40	–	54	57	48	56	52	42	58	47	23
	10	35	24	–	35	35	31	36	33	15	18	17	2
1970	04	51	43	–	57	52	40	49	49	79	–	25	15
	05	75	54	–	77	74	53	71	67	27	47	93	65
	06	106	105	–	108	106	82	108	103	91	87	146	104
	07	85	86	–	88	90	70	89	85	104	135	95	85
	08	75	70	–	77	76	57	71	71	80	65	82	64
	09	60	58	–	53	58	46	54	55	34	18	43	29
	10	43	44	–	41	44	39	43	42	60	84	13	4
1971	04	42	42	41	42	45	44	50	44	-7	–	51	–
	05	83	80	76	85	85	77	86	83	50	48	112	–
	06	96	90	76	92	91	88	89	91	89	88	113	–
	07	99	94	92	104	98	97	–	98	96	86	113	89
	08	84	78	76	85	78	77	81	81	70	63	80	58
	09	54	49	51	58	49	51	52	52	48	49	40	30
	10	42	38	40	47	42	45	49	44	26	19	18	12
1972	04	54	53	54	52	54	55	57	53	16	22	49	–
	05	78	82	79	82	87	72	80	80	58	61	99	–
	06	90	87	88	88	90	84	93	89	75	81	113	–
	07	90	94	93	91	96	92	95	93	114	119	130	–
	08	76	78	75	78	73	73	79	76	93	88	79	–
	09	54	53	48	55	54	51	55	54	38	40	40	–
	10	30	34	30	31	31	31	34	32	25	29	12	–
1973	04	55	51	57	59	52	47	61	54	26	30	53	–
	05	77	74	78	82	80	73	80	78	62	70	97	–
	06	102	99	99	104	99	97	103	101	81	76	146	–
	07	102	96	98	104	96	96	99	99	95	88	132	–
	08	82	88	88	87	88	88	85	86	93	100	98	–
	09	57	56	56	52	55	58	56	56	50	56	45	–
	10	26	27	28	25	24	28	30	27	3	1	8	–
1974	04	53	57	59	59	55	54	–	56	23	–	65	–
	05	83	84	87	87	87	83	–	85	56	66	122	–
	06	96	92	89	93	88	90	92	92	74	76	122	–
	07	93	86	83	87	84	85	88	87	87	83	109	–
	08	84	78	79	83	77	70	83	79	63	65	85	–

Table 9

Monthly evapotranspiration estimates. The left part A gives values calculated by the forest model described in earlier sections (with constants deduced from the 1974 data). Daily meteorological observations from seven synoptic stations have been used as input.

The middle part B gives values calculated by the water balance method using hydrological measurements in the Velen basin (Waldenström 1977).

To the right C are given potential evapotranspiration estimated by the Penman formula using synoptic observations at Fägre 20 km from the Velen site (Eriksson 1981) and detailed meteorological measurements in the Velen area 3 km from the site (Häggström 1973).

- It was shown by Bringfelt (1982) to be likely that lack of soil water did not reduce transpiration during 1973 and 1974. If this is so, the same conditions seem to hold during the remaining years. Then the model can be considered to give some sort of potential transpiration. If there still is lack of soil water for some months, this will be another reason for differing results.

- Figures 11b and 13 (bottom diagram to the left) show that the forest model gives higher values than the water balance especially in spring and to some extent in autumn. One possible reason for this is that the model assumes full stomatal activity (as deduced for summer mainly) while in reality the transpiration rate should be lower in spring and autumn.

- The average error in a hourly evapotranspiration value calculated from the mast data by the Bowen ratio-energy balance method was estimated by Bringfelt (1980) to ± 24 %. This is composed of errors estimated in net radiation (10 %), heat storage in soil, air and forest canopy (20 %) and the vertical gradients of potential temperature (0.03 $^{\circ}$C) and vapour pressure (0.05 mb). These errors were estimated during the data processing considering deficiencies in instruments and the siting of sensors.

  A monthly error will be smaller due to change of sign of the above errors from one hour to the next. However, the monthly error will not be much reduced since the error in some of the variables e.g. net radiation may be rather consistent for extended periods.

  These mast data form the basis of the present monthly values deduced from synoptic observations, since the model and its parameters have been adapted to the data of 1974 at the Velen site. The contribution to the error introduced by the uncertainties in synoptic data has been estimated roughly (from the scatter - about 20 % - of daily values of VCD and global radiation in figures 5 and 6) to be 5 - 10 % of a monthly value. Then the error of a monthly or seasonal value calculated by the model is estimated to be between ± 20 and ± 25 per cent.

- There are errors also in the water balance estimates. As described by Waldenström (1977), the monthly evapotranspiration E from a defined catchment (like the Velen area) was calculated by subtracting the runoff A from the area, the change ΔM of water storage in snow, lakes, soil water, and ground water from the corrected precipitation P:

  $$E = P - A - \Delta M.$$

Then, E will be a residual term containing evapotranspiration but also errors in the other measured variables.

In such a short period as one month the errors in E may be large. In summer, when the evapotranspiration is high, the errors are less important than in the other seasons. In winter, with very low evapotranspiration, the errors will predominate in the estimate of E.

In spring and autumn errors may arise in the monthly estimates due to difficulties with water storage and snow cover estimates. For example, E may have been overestimated in April and underestimated in March, if the snow cover is not properly estimated in each month. Furthermore, melting water or water from a large rainfall may still lie on the ground surface at the turn of the month. If this is not regarded properly, there will be an incorrect partition of E between the two months. This effect can be seen in figure 13 for some spring and autumn months. Averaging the monthly values over several years will reduce these errors.

Waldenström (1977) calculated the error in E as the root sum square of the errors estimated for each term. It is stated that this error calculus is uncertain since the errors may depend on each other. For the summer months this method gave an error estimate of 12 mm, corresponding to about 15 % of the evapotranspiration value E.

The factors discussed above may also contribute to the deviation from the 1:1 line in figure 10. This figure uses the averages of table 9 over the model results for six synoptic stations. It is interesting to see that the scatter has not been reduced much compared to using one single station. This seems to reflect the relatively small contribution to the error in a monthly value introduced by errors in daily synoptic data from one station.

This discussion has pointed to some further studies to be made in order to improve the model prior to practical application. This will be discussed further in the summary section below.

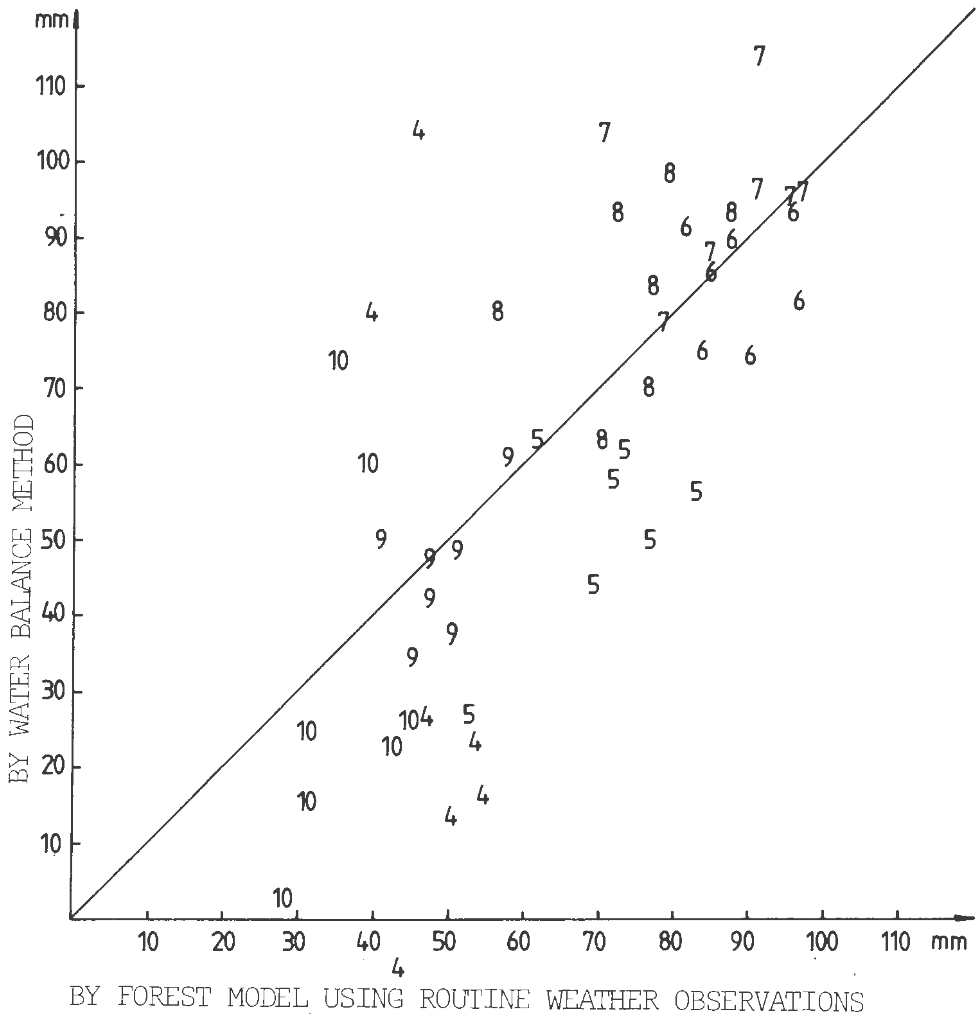


Figure 8 Monthly evapotranspiration values during 1967-1974 taken from table 9. The numbers denote month (5 = May etc). The ordinates are values calculated by the water balance method from measurements in the Velen hydrological basin.

The abscissae have been calculated for the same months by the forest evapotranspiration model using daily routine observations at Karlsborg.

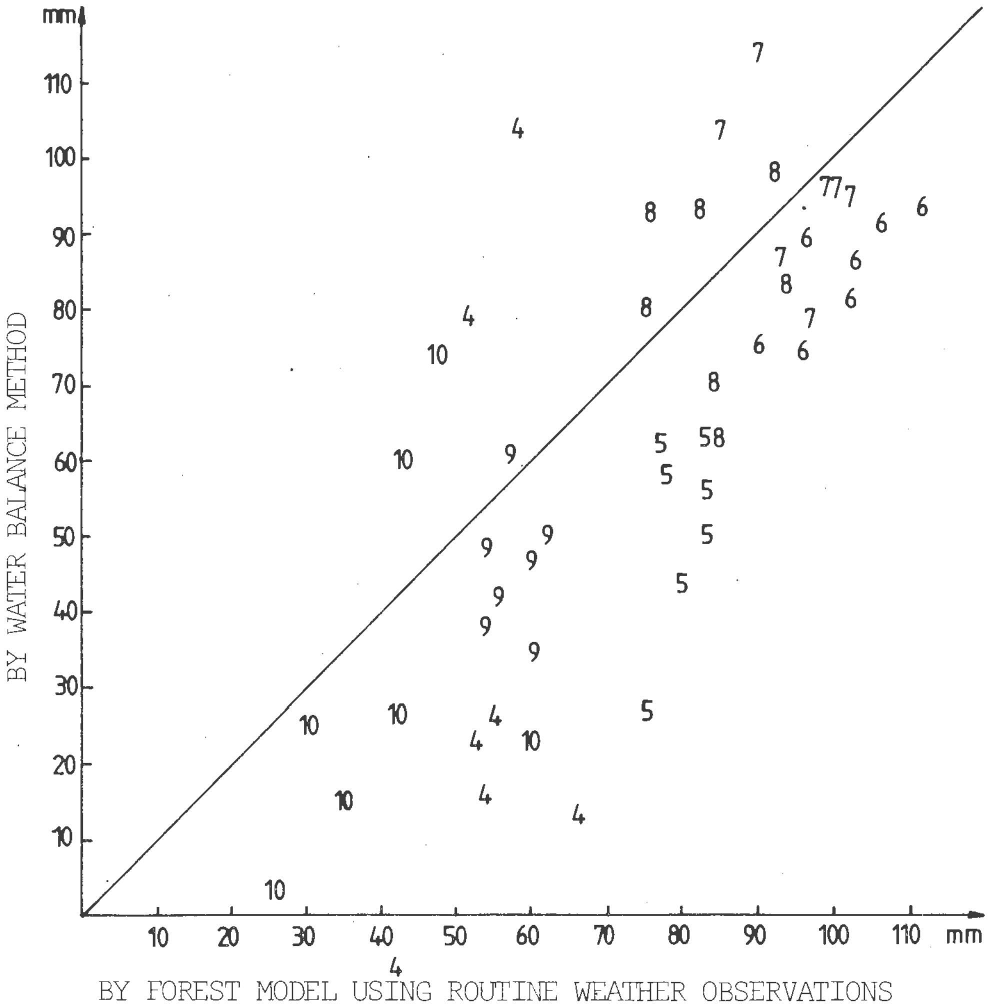
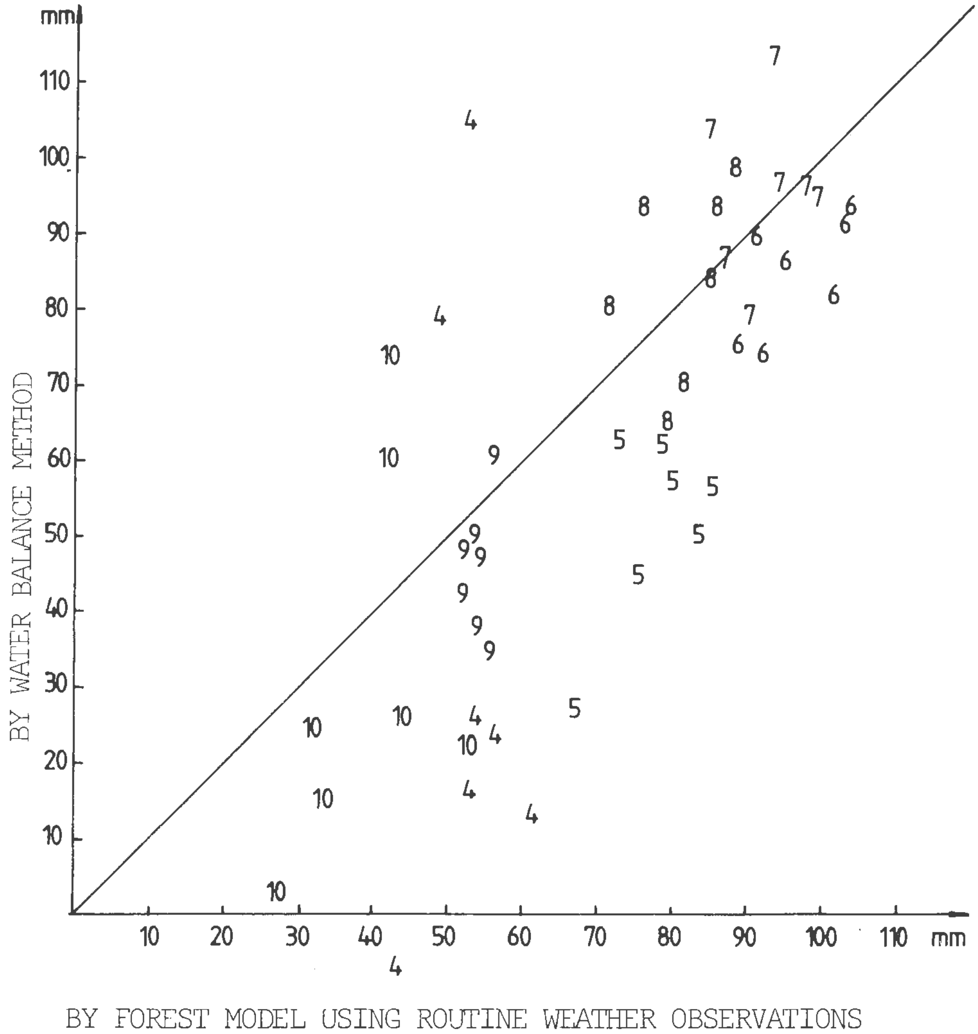


Figure 9 The same as figure 8 but observations at Ätorp have been used.



<u>*Figure 10*</u> *As figure 8 but the abscissae are averages over six values in table 9 calculated by the forest model - one for each synoptic station.*

6.2.2 Estimates by the Penman formula (with numerical example)

Estimates by the Penman formula should be compared to values of real forest water loss, keeping in mind the following:

As pointed out by Calder (1979), the "Penman equation (Penman, 1948) is a special case of the more general Monteith equation in which the equation parameters, originally derived from consideration of actual losses from grass and open water surfaces, implicitly assume values of r_a and r_s appropriate to these surfaces (see Thom and Oliver, 1977). Observed evaporation rates have often been compared with either the Penman estimate for an open water surface, E_o, or that for a freely transpiring short crop, E_t, where $E_t < E_o$".

In the Penman formula, the surface resistance r_s of the Monteith equation (see section 2) has been put equal to zero, and therefore it is stated that the result should be "the potential evapotranspiration". However, the surface resistance is near zero only for wet vegetation covers, Thom and Oliver (1977) and Stewart (1977). In dry vegetation r_s is not zero even with non-limiting soil water.

The difference between dry and wet vegetation is rather drastic for a forest. Thus, as mentioned in section 2, the rate of evaporation from a wet forest is known to be of the order of three times as large as the rate of transpiration from the dry forest in the same weather conditions.

But why does the Penman formula give reasonable estimates for many types of vegetation including forests? The answer for forest is that both its numerator and denominator are far too small.

To illustrate this, a numerical comparison between the Penman formula and the Monteith equation will be made here, using the same values of constants and input data.

The following constants for air will be used:

Density ρ	$= 1.3$ kg m^{-3}
Specific heat C_p	$= 1000$ J kg^{-1} K^{-1}
Psychrometric constant γ	$= 0.66$ mb K^{-1}

The derivative of saturation vapour pressure with respect to temperature:

$$\Delta = \frac{de_s}{dT} = 1.5 \text{ mb K}^{-1}$$

The example will use the following typical average values for daytime in summer:

Evaporation equivalent of net flux of radiant energy to the surface:

$Q = 4\ \mathrm{mm\ day}^{-1}$

Vapour pressure deficit: $e_s - e = 6$ mb

Wind speed: $u = 2\ \mathrm{m\ s}^{-1}$

The original Penman formula as given in the onset of the paper by Thom and Oliver (1977) gives

$$E_{PG} = \frac{\Delta \cdot Q + \gamma \cdot 0.26\,(e_s - e)(1 + 0.54u)}{\Delta + \gamma} = \frac{1.5 \cdot 4 + 0.66 \cdot 0.26 \cdot 6 \cdot (1 + 0.54 \cdot 2)}{1.5 + 0.66} =$$

$$= \frac{6.0 + 2.14}{1.5 + 0.66} = \frac{8.14}{2.16} = 3.77\ \mathrm{mm\ day}^{-1}$$

This corresponds roughly to $r_a = 62\ \mathrm{s\ m}^{-1}$. (Is obtained using the constants above and equating the ventilation term (second term in the numerator) to the same term of the Monteith equation).

The above Penman equation refers to short green grass, and to get anything like the potential evaporation from a forest, the ventilation term (second term in the numerator) should reasonably be increased due to the rough forest surface.

From the Monteith equation is obtained

$$E_{PF} = \frac{\Delta \cdot Q^1 + \rho C_p \dfrac{e_s - e}{r_a} \cdot 3.6 \cdot \dfrac{D}{L}}{\Delta + \gamma} \quad (\mathrm{mm\ day}^{-1})$$

D is length of day (put here to 12 hrs) and L is latent heat of vapourization ($= 2500\ \mathrm{Jg}^{-1}$). For the rough forest surface the aerodynamic resistance is of the order of $r_a = 5\ \mathrm{s\ m}^{-1}$, se Stewart and Thom (1973). If Q = 4 mm/day is multiplied by 1.23 to allow for a lower forest albedo (≈8 %) compared to grass (≈25 %), then $Q^1 = 4.91$ and

$$E_{PF} = \frac{1.5 \cdot 4.91 + 1.3 \cdot 1000\,\frac{6}{5}\,3.6\,\frac{12}{2500}}{1.5 + 0.66} = \frac{7.36 + 26.96}{2.16} = \frac{34.32}{2.16} = 15.89\ \mathrm{mm\ day}^{-1}$$

Obviously this is no useful measure of potential forest water loss. Considering the Monteith equation the value $r_s = 0$ has been used above for surface resistance, and this corresponds to wet vegetation. The high value above roughly illustrates the rapid evaporation from a wet forest discussed in section 2.

The transpiration from a dry forest E_{DF} is regulated by r_s, which is of the order of $120\ \mathrm{s\ m}^{-1}$ as obtained for the Velen forest in 1974. See also section 2.

Then the actual water loss from a dry forest using the Monteith equation

$$E_{DF} = \frac{\Delta \cdot Q^{l} + \rho C_p \frac{e_s - e}{r_a} \cdot 3.6 \cdot \frac{D}{L}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \text{ (mm day}^{-1}\text{)}$$

gives

$$E_{DF} = \frac{7.36 + 26.96}{1.5 + 0.66 \left(1 + \frac{120}{5}\right)} = \frac{7.36 + 26.96}{2.16 + 15.84} = \frac{34,32}{18.00} = 1.91 \text{ mm day}^{-1}$$

Thus, the value E_{PG} given above by the Penman formula is about twice as large as the adequate value E_{DF}. Here no rainfall was assumed. In months with high rainfall the Penman formula may even underestimate the real water loss, see Eriksson (1981).

Results of the Penman formula have sometimes been thought to be adequate mostly due to their reasonable order of magnitude. However, the above example shows that reasonable values yielded by the Penman formula are accidental for forests. This is so, because both numerator and denominator are too small (in this example by a factor of the order of 5 - 10). This is a treacherous state of the art and can lead to erroneous conclusions.

The Penman formula gives too much emphasis to incoming radiation - compare the relative magnitude of terms in the numerator of E_{PG} and E_{DF} above. Thus, the variations in radiation will have too large influence on the estimates.

The evaporation from the wet forest as well as the transpiration from the dry canopy with no shortage of soil water can be regarded as examples of potential evapotranspiration. However, none of them can be estimated by the standard Penman equation.

The bottom diagram to the right in figure 13 shows results from three studies, using the Penman formula, averaged monthly over 1967- 74 (Eriksson, 1981), 1931-60 (Wallén, 1966)* and 1968-71 (Häggström, 1973). To the left the forest model is compared with the results of the water balance method. As expected, the forest model turns out to be more successful than the Penman formula in simulating the water balance data. The Penman formula gives too large seasonal variation with too high values in summer (see numerical example above) and too low values in spring and autumn. The Penman formula disregards evaporation of rainwater intercepted on the forest canopy which has a large share in spring and autumn.

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*The paper of Wallén (1966) is used in the practical hydrological work in the SMHI.

According to the forest model the monthly interception value is rather constant in the average for the months studied, see table below. Thus the interception in per cent of the total evapotranspiration is largest in spring and autumn.

	Mean month in 1967 - 1974						
	Apr	May	Jun	Jul	Aug	Sep	Oct
Interception by forest model (mm)	15	19	12	20	17	15	19
Total evapotranspiration by model (mm)	53	81	97	93	81	54	39
Interception in per cent of total value	28	23	12	22	21	28	49

Figure 11 also compares the Penman formula (a) and the forest model (b) as regards the ability to simulate the water balance values. In both cases data from the synoptic station Fägre are used on a daily basis. The Penman estimates (table 9) were made by Eriksson (1981). The version used is a standard one intended to hold for a grass surface when water is not limiting. The comparison confirms what was said above and the suspicion by Eriksson in his paper that the Penman formula cannot give useful values for a forest.

The forest model is the more successful in simulating the water balance data as regards the average as well as the scatter. Especially for the summer months June, July and August the scatter is substantially smaller in figure 11 b.

One might expect the Penman formula to work better not using synoptic data as above but more detailed data from the Velen area itself. Very careful daily estimates were made by Häggström (1973) using humidity and wind data plus direct measurements of radiation at a site within the Velen basin (3 km from the micrometeorological site). The results are given in table 9 and for the months concerned figure 12 a shows the comparison with the water balance estimates. Figure 12 b shows that the forest model is still superior although synoptic data 20 km from the Velen area are used. Thus the scatter is smaller for the summer months in figure 12 b.

The values of Häggström seem to be low (due to low radiation input?) compared to the other Penman estimates, of figure 13.

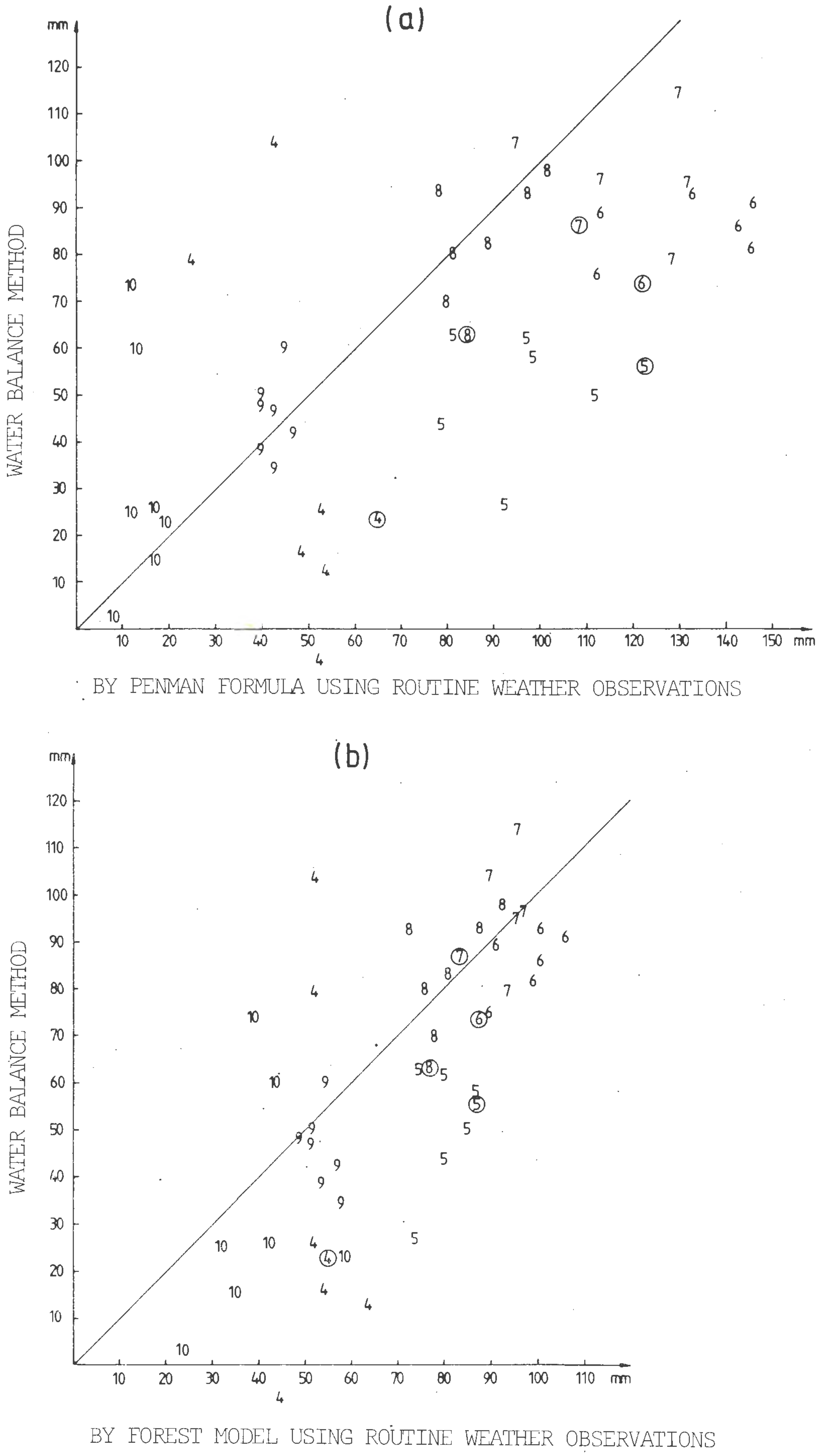

Figure 11
Monthly evapotranspiration values (mm) during 1967 - 1974. The numbers denote month (5 = May etc). The ordinates are values calculated by the water balance method from measurements in the Velen hydrological basin. The abscissae in diagram (a) have been calculated by the Penman formula using daily routine observations from the synoptic station Fägre 20 km from the Velen site. The abscissae in diagram (b) have been calculated for the same months by the forest evapotranspiration model with synoptic data from Fägre and parameter values derived from the 1974 data. The monthly points of 1974 are encircled.

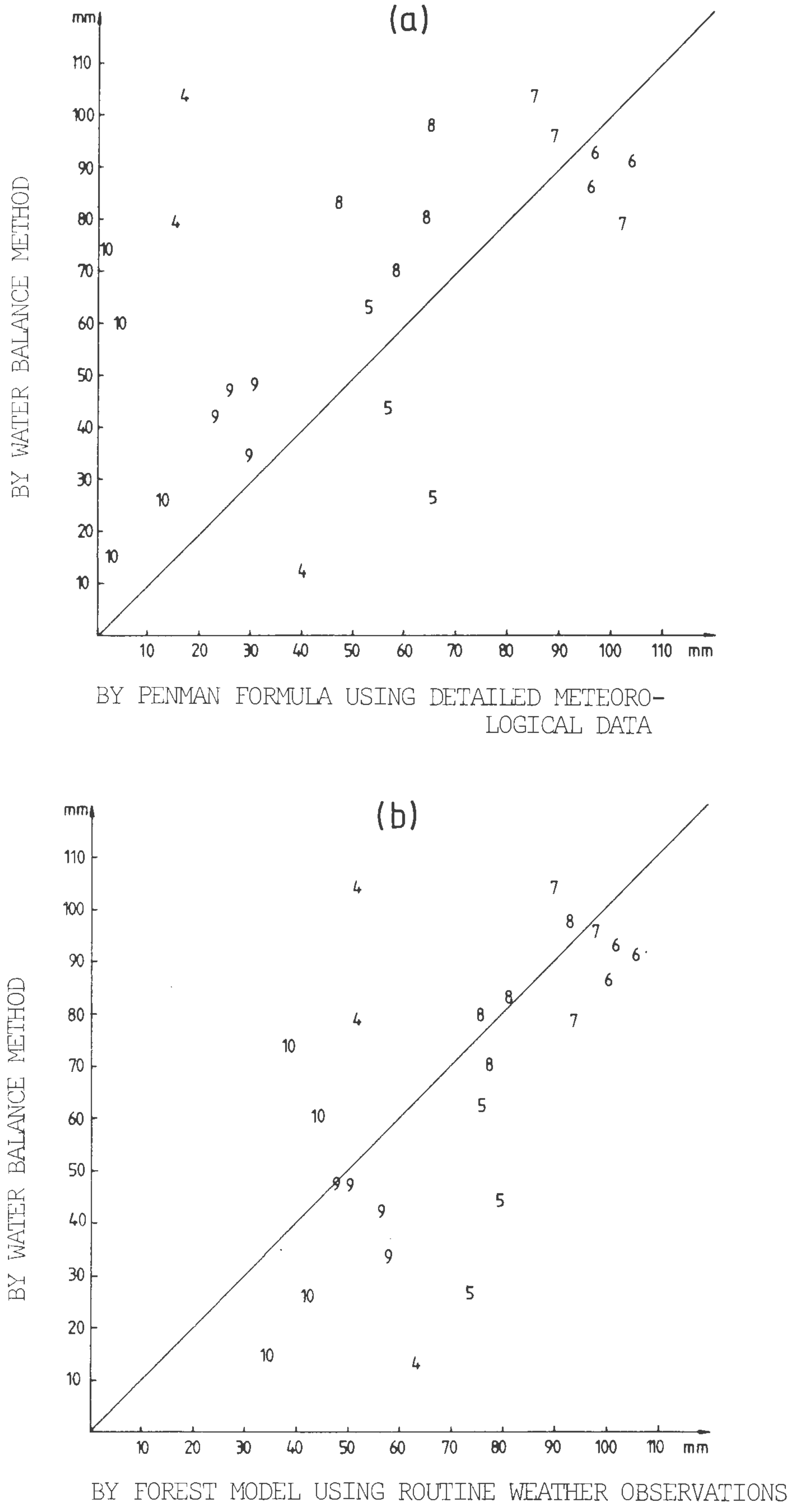

Figure 12

Monthly evapotranspiration values (mm) during 1968_71. The numbers denote month (5 = May etc). The ordinates are values calculated by the water balance method from measurements in the Velen hydrological basin. The abscissae in diagram (a) have been calculated by the Penman formula by Häggström (1973) using detailed daily data from Sjöängen 3 km from the Velen site (see table 1). The abscissae in diagram (b) have been calculated for the same months by the forest evapotranspiration model using daily routine observations from the synoptic station Fägre 20 km from the Velen site.

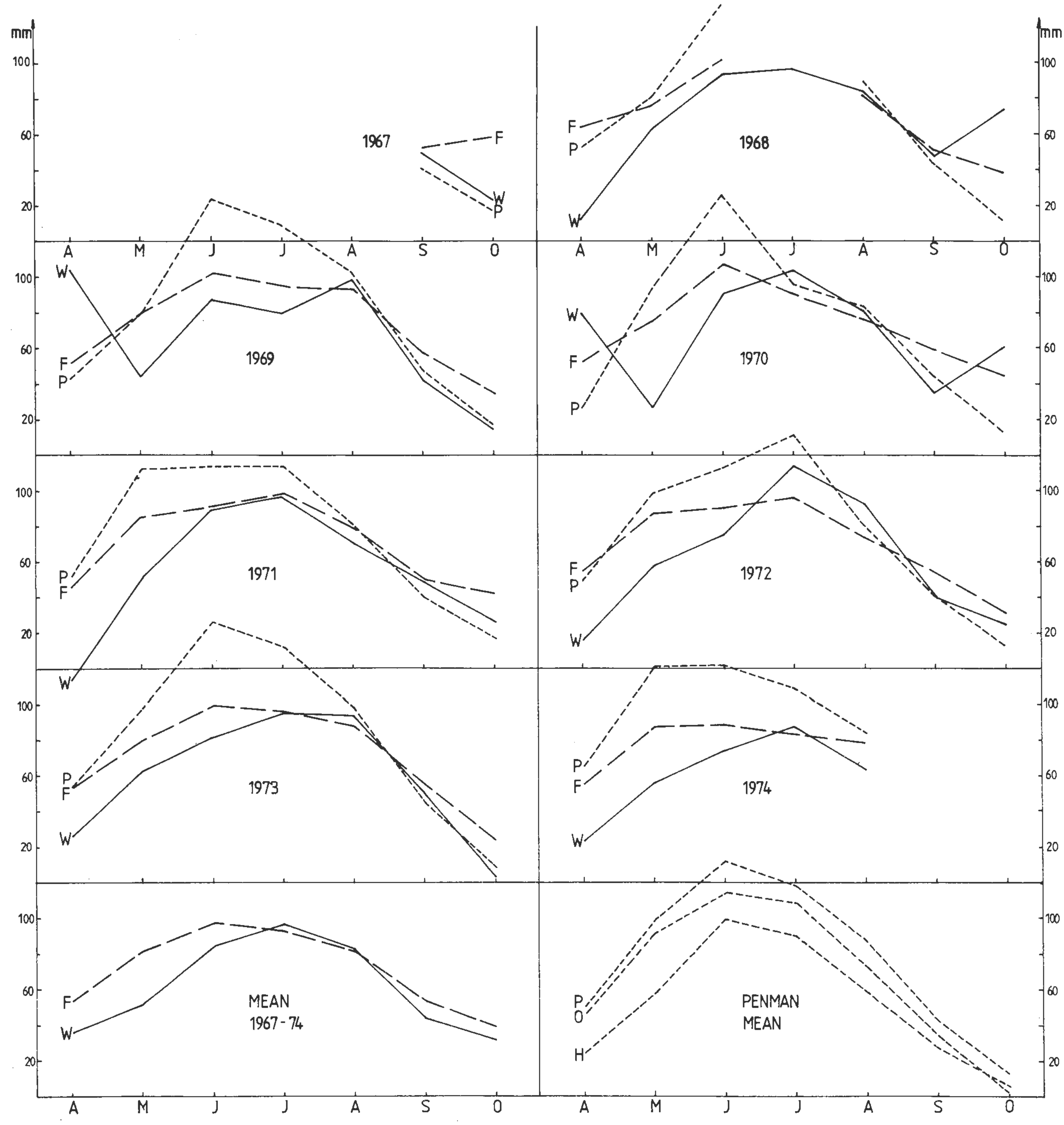

Figure 13

Monthly evapotranspiration values (mm). *In the diagrams from 1967 - 1974, based on table 9, values from the forest evapotranspiration model (F) are compared to values from the water balance method (W) and values from the Penman formula (P). Of the bottom diagrams the left gives averages over 1967-74 of the F- and W-data. The right diagram gives averages over several years of results from the Penman formula. Legend:*

W = *water balance method using measurements in the Velen basin 1967-74. Waldenström (1977).*
F = *forest evapotranspiration model using synoptic data from Fägre 20 km from the Velen site, 1967-74.*
P = *Penman formula (grass) using synoptic data from Fägre 1967-74. Eriksson (1981).*
O = *Penman formula (grass) using synoptic data from Örebro 75 km NE of the Velen area. Averages over 1931-60. Wallén (1966).*
H = *Penman formula using detailed meteorological data from Sjöängen (in the Velen basin). Averages over 1968-71. Häggström (1973).*

7. SUMMARY AND CONCLUSIONS

The following principles specific for forest evapotranspiration have been used to develop a practical model using routine synoptic data:

- Transpiration from the dry forest canopy and evaporation from the wet canopy occur at different rates and they have to be treated apart from each other.

- For a dry forest canopy the biological surface conductance k_s (or resistance $r_s = k_s^{-1}$) regulates (or suppresses) the transpiration rate. Vapour concentration deficit is the forcing factor.

- The evaporation rate from a wet forest canopy is of the order of three times as large as from the dry canopy in the same weather conditions. Important are here vapour concentration deficit, aerodynamic resistance (coupled to wind speed), the water storage capacity of the canopy and the free throughfall coefficient.

- These two different evapotranspiration rates may be expressed by the Monteith equation with values of parameters specific for forest conditions.

The model presented is based on these principles plus experience and data from the Velen forest site in southern Sweden. These measurements were made during 1973 and 1974 in a 54 m high meteorological mast. There the evapotranspiration was evaluated hourly by the Bowen ratio - energy balance method and then summed into daily values. Interception was measured by 29 rain collecting troughs below and aside the forest canopy.

Practically the computer model works on a daily basis and needs the following synoptic data:

Air humidity, temperature and total cloud cover at 06, 12, 18 GMT. (Data at 03, 06, 09, 12, 15, 18 GMT are used if available.)

Rainfall amounts over 12 hour periods reported at 06 and 18 GMT.

The submodel for evaporation of rain water intercepted on the forest canopy assumes that, within each day, daytime rainfall occurs during a time interval centered at noon and of a length related to the rainfall amount.

Using values of the free throughfall coefficient and water storage capacity of the canopy the model calculates evaporated amounts during the periods before (dependent on nighttime rainfall) and after the daytime rainfall. Thereby, the water amount stored on the canopy is assumed to decrease exponentially with time at a rate dependent on the vapour concentration deficit. The evaporation during the daytime period of rainfall is calculated assuming a constant rate (mm/hr).

The daily transpiration sums are calculated from daily averages of vapour concentration deficit and global radiation flux. Then a physiologically based relationship was used, by which k_s was found to correlate remarkably well to the above variables, see Bringfelt (1982). For days with partially wet canopy this transpiration sum is reduced.

The daytime average of vapour concentration deficit is calculated directly from the synoptic data. The daily global radiation flux is calculated by a radiation model using hourly values of solar elevation (from latitude and time) and total cloud cover.

Literature information and the data from 1974 at the Velen site were used to adapt values of the model parameters.

The interception model was tested separately against the trough measurements. Then the model was tested on data from 1973, and the calculated intercepted amounts agreed very well with the measured data.

However, the transpiration level was found to be about 30 per cent higher in 1973 than in 1974 for corresponding values of vapour concentration deficit and global radiation. The reason may be the very dry spring of 1974, which could have reduced the activity of needles and leaves and the transpiration rate that summer, see Bringfelt (1982).

No covariation could be found with soil water data. Therefore, it was considered that the soil did not, during 1973 and 1974, become dry enough to reduce the transpiration rate. The model parameter values selected for the subsequent runs were those adapted to the 1974 data.

Finally the model was run using synoptic data from each of seven stations surrounding the Velen area. This gave monthly evapotranspiration values (April - October) during 1967-74. These values were compared to independent monthly data estimated from the hydrological water balance in the Velen area. Such a comparison can be seen in figures 11 b and 13, using data from the nearest synoptic station Fägre 20 km from the Velen site.

The agreement is seen to be very good for the summer months June, July, and August. The less good agreement in spring and autumn is partly explained by uncertainties in the water balance method. Another reason is probably that the real transpiration rate is not as intensive as in the summer months (for corresponding values of vapour concentration deficit and global radiation) while, in the model, the same intensity is implicit for all months studied.

Figures 11, 12 and 13 compare the ability of the new model with that of the Penman formula as regards simulation of monthly water balance estimates. As expected, the new model agrees much better than the Penman formula with the water balance estimates.

The potential evapotranspiration from a forest can be defined in two ways:

- Evaporation from the wet canopy.
- Transpiration from the dry canopy with no shortage of soil water.

None of these situations can be simulated properly by the wellknown Penman formula in its present form.

Nor can the formula be expected to give values useful for estimating real evapotranspiration from a forest area:

It does not regard the synoptic rainfall data. Thus no interception part has been estimated, which can lead to underestimates in spring and autumn, see figure 13.

Furthermore, the Penman formula has only been developed for low vegetation, so its ventilation term is too small. Also, the surface resistance has been put to zero to simulate a potential water loss. Therefore, in transpiration from a dry forest, both its numerator and denominator are too small by a large factor. This often leads to overestimates in summer, see figure 13, but the estimates may be accidentally of a reasonable order of magnitude. It is not surprising, if the scatter is large compared to estimates of real evapotranspiration, see figures 11 and 12.

The following steps are suggested for further model studies of forest evapotranspiration:

- Make the corresponding model calculations for other areas in Sweden, where independent water balance or meteorological (Bowen ratio) estimates of forest evapotranspiration exist. Then, as in this study, synoptic data for surrounding stations and relevant periods have to be used.

- For all these areas a careful study of both water balance and other evapotranspiration data and model predictions should be made. On the basis of this study the model should be improved as much as allowed by the quality and representativity of the data.

- If possible the model should be complemented by a routine allowing for shortage of soil water to reduce transpiration. This did not seem to occur in the Velen data studied above but may be important in other parts of Sweden.

- With or without these improvements model calculation may be made for several of the 190 synoptic stations where data are available on magnetic tape. With its present parameter values, the evapotranspiration from a Velen-type of forest covering all Sweden will be obtained. Since this forest is typical for large areas, the results would probably be useful.

- To make regard of the real forest types in the various parts of the country corresponding relevant values of the model parameters should be deduced and put into the model before execution.

  The water storage capacity, free throughfall coefficient, and the transpiration formula may all be changed in order to consider a thinner forest than in Velen. Especially important and difficult is then the transpiration formula, since transpiration stands for a large part of the evapotranspiration (in the Velen material about 80 % for transpiration and 20 % for interception evaporation). The simplest way is to proportionalize from the Velen forest using leaf area index estimates. However, to get more adequate estimates over larger areas, more research is needed about transpiration rates of different forests.

- Finally the percentual forest coverage should be considered. This is rather straightforward for the interception part. The evapotranspiration from the non-forested areas may be estimated by some other method. For areas with large forest coverage this effect could probably be ignored as was the case in the present study in the Velen area.

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APPENDIX

Daily detailed data used for adapting and test of models of section 4. These data summarize the data from the Velen forest site in 1973 and 1974. Description according to the figures in the heading:

Daily input data to models:

1. Year and month.
2. Date.
3. Astronomical daylength in tenths of hours.
4. Rainfall [A)] from 1900 h the preceding day until 0700 h the present day.
5. Rainfall [A)] 0700 - 1900 h (hundreds of mm).
6. Water vapour pressure deficit in the ari measured at 16 m above ground. Daytime average in hundreds om mb.
9. Daytime global radiation sum measured above the forest canopy ($Wh\ m^{-2}$).
10. Daytime average air temperature (^{o}C).

Daily verification data

7. Daytime evapotranspiration sum obtained from mast data above the forest canopy by the Bowen ratio-energy balance method ($Wh\ m^{-2}$).

Data not used:

8. Daytime net radiation sum measured above the forest canopy ($Wh\ m^{-2)}$.

-1 means missing data.

A: Rainfall was measured in clearings by troughs and by a rainfall recorder. The 12-hourly values from the rainfall record have been increased here to correspond to the amounts given by the troughs over several days.

ÉXQT BB-PRG.MASTUT2

ÉADD,EP BB-PRG.MASTDATA

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4	7305	20	169	0	0	-1	-1	-1	-1	-1
5	7305	21	170	0	0	-1	-1	-1	-1	-1
6	7305	22	171	650	0	-1	-1	-1	-1	-1
7	7305	23	171	0	0	-1	-1	-1	-1	-1
8	7305	24	172	0	0	-1	-1	-1	-1	-1
9	7305	25	172	112	0	-1	-1	-1	-1	-1
10	7305	26	173	0	578	-1	-1	-1	-1	-1
11	7305	27	173	0	0	-1	-1	-1	-1	-1
12	7305	28	174	0	0	-1	-1	-1	-1	-1
13	7305	29	174	0	0	-1	-1	-1	-1	-1
14	7305	30	175	0	0	-1	-1	-1	-1	-1
15	7305	31	176	0	771	-1	-1	-1	-1	-1
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20	7306	5	178	0	0	-1	-1	-1	-1	-1
21	7306	6	178	0	0	-1	-1	-1	-1	-1
22	7306	7	178	0	0	-1	-1	-1	-1	-1
23	7306	8	179	0	0	-1	-1	-1	-1	-1
24	7306	9	179	0	0	-1	-1	-1	-1	-1
25	7306	10	179	588	56	-1	-1	-1	-1	-1
26	7306	11	180	0	0	-1	-1	-1	-1	-1
27	7306	12	180	0	56	-1	-1	-1	-1	-1
28	7306	13	180	0	0	-1	-1	-1	-1	-1
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136	7309	29	115	0	421	-1	-1	-1	-1	-1
137	7309	30	114	168	168	-1	-1	-1	-1	-1
138	7310	1	114	0	0	-1	-1	-1	-1	-1
139	7310	2	113	0	0	-1	-1	-1	-1	-1
140	7405	8	160	0	0	834	1394	4934	-1	11
141	7405	9	161	0	0	861	2185	4921	-1	13
142	7405	10	162	0	0	1011	2313	4707	-1	14
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151	7405	19	169	0	0	1285	2604	4935	6568	20
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157	7405	25	172	0	0	697	1715	4397	5761	13
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160	7405	28	174	56	0	646	1631	5199	7283	11
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205	7407	12	176	0	112	300	1669	2037	2765	10
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207	7407	14	175	0	2336	-1	-1	686	1024	-1
208	7407	15	174	112	0	-1	-1	2089	3854	-1
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237	7408	13	155	0	224	169	1699	1648	-1	15
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245	7408	21	148	0	0	884	1605	2910	3885	17
246	7408	22	147	0	0	708	1556	2553	3240	17
247	7408	23	146	0	0	505	1500	2458	3535	17
248	7408	24	145	0	0	495	1343	1797	2348	17
249	7408	25	144	0	0	452	1250	1875	2389	18
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258	7409	3	137	0	653	9	606	537	875	14
259	7409	4	136	0	0	312	1261	1439	2150	15
260	7409	5	135	56	913	39	998	677	874	12
261	7409	6	134	456	659	3	753	833	1108	13
262	7409	7	134	0	0	370	1885	2149	3370	16
263	7409	8	133	56	448	161	1095	1211	1503	13
264	7409	9	132	0	112	-1	-1	1906	2890	-1
265	7409	10	131	0	0	-1	-1	2262	2821	-1
266	7409	11	130	0	0	-1	-1	2106	2952	-1
267	7409	12	129	0	0	-1	-1	-1	-1	-1
268	7409	13	128	0	0	-1	-1	2066	2901	-1
269	7409	14	127	0	0	361	693	1166	1580	14
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271	7409	16	126	0	0	-1	-1	1489	2145	-1
272	7409	17	125	0	0	481	1208	1781	2440	17
273	7409	18	124	0	0	558	1814	2492	3874	13
274	7409	19	123	0	0	477	1922	2446	3321	13
275	7409	20	122	0	336	282	2185	2147	3196	11
276	7409	21	122	0	168	59	816	1066	1319	10
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279	7409	24	119	56	392	-1	-1	-1	-1	-1
280	7409	25	118	280	56	170	1189	893	1230	11
281	7409	26	117	0	0	290	1423	1769	2789	11
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283	7409	28	116	280	224	40	622	293	395	11
284	7409	29	115	0	336	178	356	475	827	10
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286	7410	1	114	0	0	-1	-1	1218	2060	-1
287	7410	2	113	0	1257	-1	-1	483	707	-1
288	7410	3	112	337	56	-1	-1	447	577	-1
289	7410	4	111	56	0	-1	-1	-1	-1	-1
290	7410	5	110	0	225	-1	-1	-1	-1	-1
291	7410	6	109	336	838	-1	-1	-1	-1	-1
292	7410	7	109	168	0	-1	-1	-1	-1	-1
293	7410	8	108	0	0	-1	-1	-1	-1	-1
294	7410	9	107	0	0	-1	-1	-1	-1	-1
295	7410	10	106	658	0	-1	-1	-1	-1	-1
296	7410	11	105	0	0	-1	-1	-1	-1	-1

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