A COMPARISON OF FOREST EVAPOTRANSPIRATION DETERMINED BY SOME INDEPENDENT METHODS

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Björn Bringfelt

SMHI Rapporter
METEOROLOGI OCH KLIMATOLOGI
Nr RMK 24 (1980)

SMHI

Sveriges meteorologiska och hydrologiska institut

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Report about the situation of the project "Development of methods to determine actual evaporation from weather data/ Utveckling av metoder att bestämma verklig av-dunstning ur väderdata".

NFR-anslag G 3795-103

SVERIGES METEOROLOGISKA OCH HYDROLOGISKA INSTITUT
Norrköping 1980

ISSN 0347-2116

Tryckt på SMHI:s tryckeri 1980

SUMMARY

Results are described on actual forest evapotranspiration in the Velen hydrological representative basin in Sweden and some measuring methods have been compared. The evapotranspiration obtained by the Bowen ratio method for two summer seasons (using mast data from the layer above the forest) was found to be 25% larger than that obtained by the water balance method. The difference lies within the error limits except for May and June.

The 133 daily values obtained by the Bowen ratio method were found to be related to those of an evaporation pan according as rain had fallen or not in the preceding days and nights. This illustrates the role of the "forest water status" and also that a pan cannot be used as indicator of some "forest potential evapotranspiration".

The techniques of measuring forest evapotranspiration are discussed, and it is pointed out that different methods often give different results. Therefore, it is important to check the measurements rigorously and to control the forest water and energy balance.

The final report to appear later will contain data on the surface resistance of the forest. Generalization to other periods will be made using simple routine observations.

SAMMANFATTNING

Resultat beskrivs rörande aktuell avdunstning från skog i det hydrologiska representativa området Velen och några olika mätmetoder har jämförts. Evapotranspirationen erhållen ur Bowenförhållandemetoden för två sommarsäsonger (med mastdata tagna ovanför skogen) var 25% större än vad vattenbalansmetoden gav. Skillnaden ligger inom felgränserna utom för en maj-och en junimånad.

De 133 dygnsvärdena erhållna med Bowenförhållandemetoden förhöll sig till värdena från en avdunstningstank på ett sätt som berodde på om det hade regnat eller ej de senaste dygnen. Detta illustrerar betydelsen av "skogens vattenstatus" och även att en tank inte kan användas som indikator på "skogens potentiella evapotranspiration".

Metoderna att mäta avdunstning från skog diskuteras och det påpekas att olika metoder ofta ger olika resultat. Därför är det viktigt att noga följa upp mätningarna och att ha kontroll på skogens vatten- och energibalans.

Den kommande slutrapporten för projektet skall innehålla data över skogens ytresistans. Generalisering till andra perioder kommer att göras där man utnyttjar enkla rutinobservationer.

PREFACE

This report describes evapotranspiration measured directly in a forest in the Velen hydrological representative basin in Sweden. These detailed measurements were made in 1973 and 1974 in the earlier project "Measurements of Evaporation from Forest (Representative basin Velen)" IHD-project No 19. The final report of that project appeared in 1977 and describes the site, instruments, methods, data and some results.

In this report monthly evapotranspiration data obtained by the different direct methods are compared. The final report is planned to appear in 1981 and will contain data on the surface resistance of the forest derived from the direct evapotranspiration data. It will also contain generalization to other periods using simple routine observations.

Sten Laurin, SMHI, has solved the difficult task of interpreting and making useful the humidity profile data. Arne Forsman, Todor Milanov och Torbjörn Jutman, SMHI, have given valuable advice in treating the water balance and pan data.

Constructive comments to section II have been given by Sven Halldin and Per-Erik Jansson, Uppsala.

CONTENTS

INTRODUCTION

This report will describe the results of the project so far. The project will have reference to evaporation only from forest, see application to the Swedish National Research Council (NFR) of 1979-01-25.

In this report will be presented and compared evaporation values for the Velen forest obtained by different methods. A description of the Velen site, instruments, methods and some results is given in ref. No 1.

Based on the comparisons of this report, methods will be developed to calculate real evaporation from the Velen forest using the detailed data collected in 1973 and 1974. For example the comparisons will give material for discussion of what value to use for the ratio of the turbulent exchange coefficients for heat and water vapour in connection with the Bowen ratio method. This method is the most widely used micrometeorological method for calculating evaporation. So far we have used the value $K_H/K_E = 1$.

When the best method has been agreed upon, we will calculate real evaporation values from the Velen data of 1973 and 1974, and use them to proceed to the goal of establishing evaporation formulae, where common weather data can be utilized.

I ESTIMATED EVAPOTRANSPIRATION FROM THE VELEN AREA FOR 1973 AND 1974

Methods used

Five independent methods have been used:

1. Bowen ratio method

2. Eddy correlation method

3. Pan method

4. Water balance method

5. Trough method

For this five methods table 1 gives the data which have to be used and the kind of evaporation obtained.

Methods 1, 2, 3 and 5 have been described in detail in reference No 1 and in further references given here. Method 4 has been described and applied in the Velen area in ref. No 3. Only some important features of the methods will be described here.

Table 1. Five methods to estimate forest evaporation and data used. The results will be of different kinds for the different methods see top of table. The typical time average is given in the middle. For some methods two or more sources of data are needed. This has been marked by a connecting vertical bar.

Kind of evaporation obtained	Real evaporation from the forest			Tank evaporation	Evaporation of rain water intercepted on the canopy
Method / Data used	Bowen ratio method	Eddy flux method	Water balance method	Tank method. Subtraction of water levels read at two time points	Trough method. Evaporation = Total rainfall - throughfall
Profiles above forest of temperature and humidity	Hour				
Net radiation above forest	Hour				
Heat storage in air canopy and soil	Hour				
Rapid fluctuations above forest of humidity and vertical wind speed		Hour			
Values of rainfall, runoff and storage in the basin			Month		
Values of water level in tank GGI 3 000				One day	
Values of total rainfall (troughs, rainfall recorder and accumulator)					Week
Values of throughfall (troughs)					Week
Rainfall record	Used througout	Used througout	Used througout	Used througout	
Wind speed and direction	"		"		

1. Bowen ratio method

In ref. No 1 evaporation values were presented for August 1974 only. There, evaporation values were estimated roughly for the seven days with poor or no raw data, in order to get a figure for the whole month. In the present work values will be evaluated by the Bowen ratio method using good mast data from 133 days in eight of the summer months of 1973 and 1974. At first hourly evaporation values were determined. Then they were summerized into daily values. In table 2 all daily values calculated directly by the Bowen ratio method are given without brackets. The values for days with no or poor mast data have been calculated by a method using also the tank data (values in brackets) see discussion below.

Table 7 contains hourly Bowen ratio method evaporation values calculated at occasions of eddy flux measurements.

In using the Bowen ratio method the following important two steps have been taken as to the data processing:

A. A method to correct the humidity profiles has been applied:

When the resistance thermometers are operating, the errors in vapour pressure profiles are mainly due to incomplete wetting of the wet-bulb thermometers. The resulting errors are proportional to the wet-bulb depression.

To get a correction for this error, the following technique was used. In some occasions, the box containing dry- and wet-bulb thermometers was disconnected from the tube system of the mast. When all thermometers were sensing identical temperature and humidity conditions, corrections could be established.

The possibility of all wet-bulbs being too dry will not complicate the analysis since we are only interested in the profiles of vapour pressure and therefore only need an absolute correction relative to one of the wet-bulb sensors (chosen to be reference sensor).

During normal operation the proper corrections can be obtained by taking the corrections from the latest check occasion and multiply with actual wet-bulb depression divided by the wet-bulb depression from the check.

The fact that originally irregular profiles became very smooth after this correction procedure has been taken as a justification of the method and its assumptions.

B. A working formula for the energy storage in soil, canopy and air has been developed:

In ref. No 2 detailed information is given about the measurements of heat storage in canopy, soil and air. The rate of heat storage was calculated from temperature records at 40 points.

Table 2. Daily values E with estimated errors dE of evaporation from the Velen forest obtained by the Bowen ratio method. The values in brackets have been estimated by a method using also evaporation readings from the pan GGI 3 000.
The values are in mm.

	July 1973		Aug 1973		Sept 1973		May 1974		June 1974		July 1974		Aug 1974		Sept 1974	
	E	dE	E	dE	E	dE	E	dE	E	dE	E	dE	E	dE	E	dE
1	(3.6	1.2)	4.1	0.6	2.6	0.7	(3.3	1.1)	3.4	1.1	(3.7	1.2)	3.2	0.9	2.8	0.6
2	(3.5	1.2)	4.6	0.6	4.2	1.0	(3.6	1.2)	2.4	0.6	(3.7	1.2)	2.0	0.4	2.5	0.4
3	(4.0	1.2)	4.0	0.5	3.5	0.8	(3.6	1.2)	4.4	0.9	(3.7	1.2)	3.7	0.7	0.5	0.1
4	(3.7	1.2)	2.3	0.3	(2.7	1.0)	(3.6	1.2)	4.0	1.2	(2.7	1.0)	3.1	0.8	2.2	0.5
5	(3.5	1.2)	2.4	0.4	1.4	0.8	(3.5	1.2)	3.7	1.3	(2.6	1.0)	3.5	0.8	1.2	0.6
6	(3.8	1.2)	2.9	0.4	3.7	0.9	(3.5	1.2)	(3.2	1.1)	(3.9	1.2)	2.8	1.1	1.0	0.2
7	(3.3	1.1)	5.1	0.6	3.2	0.8	2.5	0.9	(2.6	1.0)	(2.7	1.0)	2.8	1.1	3.0	0.4
8	(3.5	1.2)	3.5	0.6	3.1	0.5	3.0	0.9	(2.6	1.0)	(3.3	1.1)	3.1	1.1	1.4	0.3
9	(3.3	1.1)	5.4	0.7	2.1	0.6	3.7	0.9	(3.7	1.2)	(3.5	1.2)	3.1	0.5	(2.5	1.0)
10	(4.0	1.2)	2.7	1.3	(3.3	1.1)	3.9	0.9	(2.6	1.0)	(3.5	1.2)	1.4	0.2	(2.1	0.9)
11	(2.7	1.0)	3.4	0.8	(2.7	1.0)	3.8	1.2	(2.3	0.9)	2.4	1.0	2.6	0.4	(1.8	0.8)
12	(2.7	1.0)	3.8	0.9	(3.2	1.1)	3.1	1.0	(3.6	1.2)	1.5	0.7	4.4	0.6	(2.7	1.0)
13	(2.7	1.0)	(3.2	1.1)	2.2	1.1	3.1	1.2	(3.8	1.2)	2.8	0.7	2.8	0.4	1.6	0.4
14	2.4	1.0	(3.6	1.2)	1.5	0.5	(3.6	1.2)	(3.7	1.2)	0.7	0.1	(2.3	0.9)	0.9	0.5
15	4.4	1.1	(3.2	1.1)	1.7	0.8	(3.3	1.1)	(3.4	1.1)	(3.4	1.1)	(0.8	0.5)	0.3	0.4
16	3.1	1.1	(3.3	1.1)	2.5	0.4	2.0	0.4	(3.9	1.2)	(1.7	0.8)	(2.4	1.0)	0.5	0.4
17	(3.1	1.1)	(3.6	1.2)	1.5	1.0	4.4	0.9	(3.9	1.2)	3.4	0.5	(3.3	1.1)	1.7	0.7
18	(3.8	1.2)	(4.1	1.2)	(2.4	1.0)	4.8	0.8	(3.7	1.2)	2.3	0.5	(3.4	1.1)	2.4	0.9
19	(3.4	1.1)	3.6	0.9	2.4	0.8	4.7	0.8	(3.3	1.1)	3.5	1.0	(2.8	1.0)	2.5	0.8
20	4.5	0.6	3.5	0.8	0.6	0.3	4.0	0.7	(3.6	1.2)	2.4	1.5	3.6	0.6	3.1	0.8
21	4.1	0.5	(3.9	1.2)	(3.1	1.1)	(2.6	1.0)	(2.1	0.9)	2.6	1.0	2.5	0.4	1.0	0.3
22	3.8	0.5	(3.8	1.2)	(2.3	0.9)	(3.4	1.1)	(3.4	1.1)	1.1	0.5	2.3	0.4	(1.5	0.7)
23	5.1	0.6	(2.8	1.0)	(1.7	0.8)	4.0	0.9	(3.2	1.1)	3.2	0.9	2.1	0.4	(2.2	0.9)
24	4.0	0.5	(3.3	1.1)	(1.4	0.7)	3.4	1.0	(3.5	1.2)	2.7	0.6	1.7	0.4	(2.1	0.9)
25	(3.3	1.1)	(3.2	1.1)	(1.9	0.8)	2.7	0.8	(3.5	1.2)	2.3	0.7	1.5	0.4	1.3	0.3
26	2.4	0.3	2.8	1.1	(1.9	0.8)	2.9	0.8	(3.9	1.2)	3.0	0.7	3.1	0.5	2.0	0.4
27	3.4	0.5	(2.3	0.9)	(2.3	0.9)	3.4	0.7	(3.1	1.1)	3.5	0.5	1.5	0.8	1.6	0.3
28	5.2	0.6	(2.5	1.0)	(2.3	0.9)	2.8	0.9	(2.6	1.0)	4.3	0.8	1.0	0.1	0.3	0.1
29	5.6	0.7	(2.2	0.9)	(3.1	1.1)	2.5	0.4	(3.5	1.2)	3.1	0.9	3.4	0.5	0.5	0.2
30	4.7	0.6	(2.7	1.0)	(1.0	0.5)	4.1	0.7	(3.3	1.1)	2.4	1.2	1.7	0.7	(1.7	0.8)
31	(3.0	1.1)	1.8	0.4			(4.1	1.2)			(3.3	1.1)	(2.6	1.0)		
Sum.	114	± 29	104	± 27	72	± 25	107	± 29	100	± 33	89	± 28	81	± 21	51	± 17

The heat storage rate $S(Wm^{-2})$ was evaluated for August 1974 only. From these data the ratio $\frac{S}{Q}$ was calculated for each hour of the days. It was found that the following expressions were in good agreement with the data set:

$$S = [(12-h)0.02+0.07]Q \text{ when } Q > 150 \text{ Wm}^{-2}$$

$$S = [(12-h)0.02+0.13]Q \text{ when } 0 < Q \leq 150 \text{ Wm}^{-2}$$

$$S = \max(Q, -20) \qquad \text{when } Q < 0$$

Where h is the hour of the day and Q is net radiation.

Later the expressions were tested for the eleven sunny days used in ref. No 2. The expressions still showed a good performance.

2. Eddy correlation method

An x-wire anemometer was used to get the fluctuations of the horizontal and vertical wind components.

The temperature fluctuations were measured by a platinum resistance thermometer. The humidity fluctuations were measured by a Lyman -alfa humidiometer. See further ref. No 1.

3. Pan method

At Sjöängen, 3 km from the mast, daily water levels have been read in two pans, GGI 3 000 and Class A pan. This observation site is in a garden close to the forest and a lake.

Here the GGI 3 000 has been used throughout since the Class A pan showed larger day - to - day variations. Daily values from 1973 and 1974 shown in table 3. In principle, the pan method can never be expected to give evaporation from a forest. A comparison between the Bowen ratio method and the pan method will be made below.

Table 3. Daily evaporation readings from the pan GGI 3 000 at Sjöängen in the Velen area during 1973 and 1974. The values are in mm.

Day	May 1973	June 1973	July 1973	Aug 1973	Sept 1973	Oct 1973	Apr 1974	May 1974	June 1974	July 1974	Aug 1974	Sept 1974	Oct 1974
1	1.9	1.5	4.0	3.0	1.5	0.5		2.9	2.7	4.5	4.5	2.7	0.9
2	2.8	2.4	3.5	2.9	2.4	1.2		3.8	3.4	4.5	0.7	1.5	0.8
3	2.1	2.1	6.1	2.1	2.5	0.8		3.8	3.0	2.6	3.0	0.1	0.2
4	2.5	2.0	4.6	3.1	1.9	1.0		4.1	4.2	2.0	3.0	2.5	0.4
5	0.5	2.5	3.7	2.1	1.0	0.4		3.4	3.7	1.9	2.9	1.0	0.6
6	1.5	3.4	4.9	2.6	1.6	0.9		3.5	2.8	2.9	3.1	0.2	0.7
7	1.0	3.9	3.0	2.6	3.0	0.4		3.4	1.9	2.0	3.9	1.9	0.9
8	0.6	3.5	3.7	2.6	1.9	0.2		3.4	1.9	3.0	3.1	1.2	0.6
9	1.6	4.6	3.0	3.2	2.5	0.3		2.8	2.6	3.5	1.0	1.7	2.1
10	1.9	2.4	3.4	0.8	3.0	0.8		3.7	1.8	3.5	4.2	1.3	0.4
11	1.9	4.5	2.0	2.4	2.0			3.9	1.7	3.0	3.5	1.0	
12	2.6	1.7	2.0	2.5	2.7			2.2	4.0	2.3	2.0	2.0	
13	1.1	3.1	2.0	2.7	1.4			5.3	4.7	1.5	1.1	0.5	
14	2.9	3.9	2.0	3.8	1.4			4.1	4.4	1.0	1.5	1.5	
15	3.0	4.0	3.0	2.7	0.5			3.0	3.3	2.0	0.4	0.9	
16	3.1	3.7	1.6	3.0	1.6			1.6	5.5	0.8	1.6	1.0	
17	3.7	4.1	2.5	3.9	2.0			3.0	5.7	2.0	1.9	1.0	
18	1.1	3.9	2.8	3.7	1.6			3.0	4.2	1.6	2.1	2.1	
19	1.8	4.3	3.2	3.0	1.9			6.0	3.0	2.3	2.2	1.0	
20	2.6	4.1	3.2	3.1	1.7		1.8	3.1	4.0	3.2	3.8	1.5	
21	0.9	5.4	2.9	3.0	1.7		2.0	1.8	1.5	4.2	2.4	0.9	
22	1.0	4.1	2.1	2.8	1.7		2.1	3.1	2.0	1.8	1.9	1.0	
23	1.6	4.2	3.6	2.2	1.2		2.0	3.7	2.8	2.5	1.1	1.6	
24	1.9	3.3	1.8	2.9	0.6		1.8	3.1	3.5	2.0	1.1	1.0	
25	1.4	3.9	3.0	2.7	1.1		1.9	2.7	3.5	1.3	1.2	1.0	
26	1.9	3.4	1.1	2.4	1.1		1.9	2.3	5.6	2.4	1.8	0.7	
27	1.0	2.6	1.5	1.5	1.5		2.1	2.9	1.7	1.8	3.6	0.5	
28	1.6	1.0	2.7	1.7	1.7		2.9	3.6	1.9	3.5	0.4	0.5	
29	2.3	1.5	3.0	1.3	1.7		3.0	1.6	1.5	3.4	1.8	0.5	
30	3.7	3.5	3.3	1.9	0.4		3.2	2.5	3.0	3.0	1.9	1.2	
31	1.9		2.4	1.1				3.5		3.1	1.9		
Sum.	59.4	98.5	91.6	79.3	50.8			100.8	95.5	79.1	68.6	35.5	

4. Water balance method

A map of the Velen runoff area and its sub runoff areas is given in figure 1. A detailed description of the data and use of the water balance method for these areas and the years 1967 - 76 is given in ref. No 3. The results for the entire Velen basin and the Nolsjön sub basin where the micrometeorological mast is situated are given in tables 4 and 5.

Precipitation and soil water content were measured at seven sites in the Velen area. Errors in the water balance method were discussed in ref. No 3 and will also be estimated below.

5. Trough method

This method gives evaporation of intercepted rain water only. Data have been collected in the Velen forest during May - Sept in 1973 and 1974. The results for 1973 were published in ref. No 4. The 1974 data were given in ref. No 1. In the left part of table 6 below these data from 1973 and 1974 are summerized.

In ref. No 4 is found a description of the troughs used and their siting. Four troughs were operating in clearings and 25 troughs were sited below the forest canopy.

Readings to the water amounts caughts were made every one or two weeks, see table 6. To determine the amount of water intercepted by the forest canopy the difference was taken between the precipitation of troughs in clearings and troughs below the canopy.

A simple interception model was developed and described in ref. No 4 and this model was used here to transform the data for the operating periods into monthly interception data. This procedure can be studied in table 6.

<u>Figure 1</u>. Velen hydrological represenative basin with sub basins.

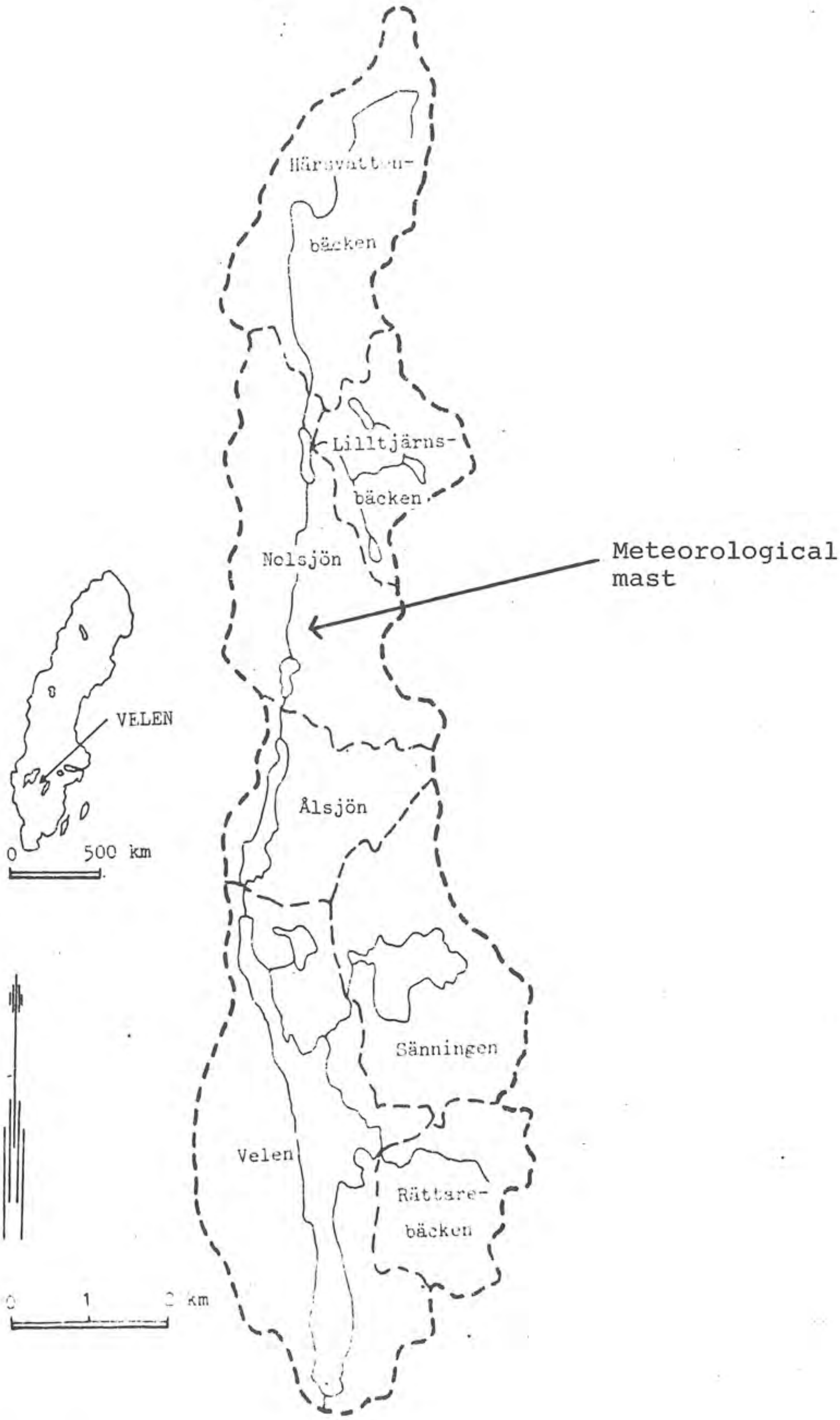


Table 4. Monthly water balance in mm for the entire Velen basin. From Waldenström 1977.

	1973					1974				
	May	June	July	Aug	Sept	May	June	July	Aug	Sept
Corrected rainfall	62	26	72	65	68	18	64	64	57	92
Runoff	12	6	1	0	0	8	2	0	0	0
Monthly change in										
lake water storage	-1	-12	-5	-4	0	-12	-5	-4	-3	+4
soil water storage	-7	-28	-12	-19	+9	-20	+1	-11	-2	not measured
subsoil water storage	-4	-21	-7	-5	-1	-14	-8	-8	-2	+5
Residue term = evaporation from the Velen basin	62	81	95	93	60	56	74	87	63	-

Table 5. Monthly water balance in mm for the Nolsjön sub basin. From Waldenström 1977.

	1973					1974				
	May	June	July	Aug	Sept	May	June	July	Aug	Sept
Corrected rainfall	63	21	83	77	65	15	69	57	75	-
Runoff	9	2	0	1	0	2	0	0	1	-
Monthly change in										
lake water storage	0	-2	0	0	0	-2	0	0	1	-
soil water storage	-11	-31	-2	-19	11	-29	3	-18	4	-
subsoil water storage	-5	-24	-3	-5	-2	-22	-10	-8	4	-
Residue term = evaporation from the Nolsjön sub basin	70	76	88	100	56	66	76	83	65	-

Table 6. Data of rainfall and throughfall and intercepted rain water in the Velen forest in 1973 and 1974. The right part of the table gives calculated monthly data. The values are in mm.

1973:	Rainfall (mean of 4 troughs in clearings) (R)	Throughfall (mean of 25 troughs below canopy) (T)	Difference = intercepted rain (I = R - T)	Monthly intercepted rain: May	June	July	Aug	Sept
0517 - 21	3.3	1.7	1.5	1.5				
0521 - 22	6.5	4.5	2.0	2.0				
0522 - 0604	23.2	14.2	9.0	5.3	3.7			
0604 - 19	7.0	4.2	2.8		2.8			
0619 - 0719	36.1	27.1	9.0		1.8	7.2		
0719 - 26	62.2	55.0	7.2			7.2		
0726 - 0815	56.5	39.9	16.6			2.0	14.6	
0815 - 20	11.6	9.5	2.1				2.1	
0820 - 0904	16.4	11.0	5.3				3.8	1.5
0904 - 12	2.9	1.2	1.7					1.7
0912 - 19	0.8	0.3	0.5					0.5
0919 - 21	17.7	14.3	3.4					3.4
0921 - 25	25.2	17.9	7.3					7.3
0925 - 1002	18.4	13.1	5.3					5.3
			Monthly interception 1973	-	8.3	16.4	20.5	19.7
1974:				May	June	July	Aug	Sept
0501 - 28	4.9	2.8	2.1	2.1				
0528 - 30	12.1	7.6	4.5	4.5				
0530 - 0611	16.2	8.6	7.6	0.2	7.4			
0611 - 25	40.3	32.6	7.7		7.7			
0625 - 0711	24.7	18.1	6.6		2.0	4.6		
0711 - 16	25.6	20.5	5.1			5.1		
0716 - 24	8.7	4.6	4.1			4.1		
0724 - 26	4.0	2.2	1.8			1.8		
0726 - 30	15.8	12.3	3.5			3.5		
0730 - 0809	0.7	0.4	0.3			0	0.3	
0809 - 20	62.7	48.6	14.1				14.1	
0820 - 0904	21.9	14.7	7.2				2.6	4.6
0904 - 17	27.0	19.4	7.6					7.6
0917 - 1010	90 [1)]	71.2	20 [1)]					15 [1)]
			Monthly interception 1974	6.8	17.1	19.1	17.0	27 [1)]

[1)] Rough values due to missing trough data.

Comparison of Bowen ratio method and eddy correlation method.

Table 7 shows the data taken at 38 periods. As can be seen, most of the periods were about one hour of length. Some of them were shorter, down to 15 - 20 minutes. Most of the periods are consecutive and then the data were recorded on the same day in one single run of two or more hours. There are nine different days from which complete data exist.

Figures 2, 3 and 4 show the energy flux values compared in different ways. The common feature is that the fluxes obtained by the eddy correlation method are smaller than those obtained from the net radiation data.

Looking at figure 4 only, one could suspect that the reason for the fact that the Bowen ratio evaporation values are larger than the eddy correlation values, is that the value of unity used for K_H/K_E is too small. If a value of K_H/K_E around 1.3 is used, then there would be agreement in the mean. However, the consequence would be that the values of H_{BOWEN} would be still larger in figure 3.

It is also evident from figure 2 that the deviation occurs even without using the Bowen ratio at all.

Apart from effects due to inadequate site (see below) there seems to be only the following two possible instrumental causes for the deviation.

1. The net radiation is too large.

2. The eddy correlation method gives too small values.

It does not seem possible that an error in net radiation alone can be the reason for errors of this magnitude since that error can hardly exceed 10%, see ref. No 1.

If there are errors in the eddy correlation estimates, there is probably some error which has to do with the construction of the wind instrument. This is so because both latent and sensible heat flux are too small. Probably the error is not due to insufficient time constants, or too long distance between sensors or too large sensors, since very rapid and small instruments have been used in relation to the large eddies that are known to occur over a forest.

A special investigation of the vertical angles of the wind showed that these angles may often exceed 30° and even 45° which is the slope of the hot wires.

Already for winds sloping 30° to the horizontal there are disturbances in the signals and for larger angles the signals of the X-wire anemometer were seen to be useless. Due to that reason the eddy correlation fluxes presented here can be regarded only as lower limits for the proper values.

It could be possible to evaluate the upper limits. If these upper limits (ordinates) still lie below the line 1:1 (drawn in the figures), then there would be reason to assume that the values obtained by the net radiometers (abscissae) and thus the Bowen ratio method are too large. This study has not been considered worthwhile because of the fact that the raw data are inadequate. However, some visual studies of the turbulence records and rough estimates indicate that the upper limits are probably considerably larger than the lower limits presented here. In that case there would have been no reason to say that the Bowen ratio method has given too large values.

Before start of these measurements, the X-wire anemometers had been used only over plane fields, where the slopes of the wind are smaller. When planning for use of these anemometers there was no information that they could not be used over forest.

Table 7. Hourly data from the eddy correlation measurements above the Velen forest and data for the Bowen ratio method taken at the same site and periods.

The data can be divided into three groups:

I Results from the eddy correlation measurements.

II Results from the micrometeorological measurements intended for the Bowen ratio method.

III Reference data such as stability values.

		I						II										III			
Date	Time	H_{EDCOR} Wm^{-2}	E_{EDCOR} Wm^{-2}	U_* ms^{-1}	Q Wm^{-2}	S_C Wm^{-2}	S_M Wm^{-2}	$\gamma \frac{\Delta\Theta}{\Delta e}$ 29–34 m	$\gamma \frac{\Delta\Theta}{\Delta e}$ 16–29 m	$\gamma \frac{\Delta\Theta}{\Delta e}$ 16–34 m	H_{BOWEN}, Wm^{-2} 29–34 m	E_{BOWEN}, Wm^{-2} 29–34 m	E_{BOWEN}, Wm^{-2} 16–29 m	E_{BOWEN}, Wm^{-2} 16–34 m	$\frac{\partial u}{\partial z}$ ms^{-2}	$\frac{z-d}{L}$	Ri	ϕ_M	ϕ_H	ϕ_E	ϕ_E/ϕ_H
730906	12 - 13	163	247	.531	463	51	–	2.48	0.56	0.98	294	118	264	208	(.13)	-.201	-.060	(1.61)	.77	.21	.27
	13 - 14	154	286	.562	450	41	–	1.20	0.68	0.86	223	186	243	220	(.13)	-.161	(-.044)	(1.52)	.63	.29	.46
730919	11.23 - 12	100	87	.717	307	40	–	1.54	1.14	1.71	162	105	125	99	.159	-.051	-.019	2.54	.79	.60	.76
	12 - 12.17	183	106	.610	397	48	–	2.86	(1.25)	(2.28)	259	90	155	106	.144	-.151	-.043	1.55	.68	.42	.62
	14.34 - 15	132	105	.623	265	16	–	1.32	(0.54)	(1.68)	142	107	162	93	.146	-.102	-.019	1.54	.45	.44	.98
	15 - 15.29	13	77	.508	200	10	–	0.66	(0.11)	(0.49)	76	114	171	128	.135	-.019	.011	1.77	1.82	.48	.26
731003	11 - 12	77	115	.363	266	35	–	–	–	–	–	–	–	–	(.11)	-.300	(-.056)	(1.99)	.74	–	–
	12 - 12.45	78	136	.508	210	23	–	–	–	–	–	–	–	–	(.11)	-.111	(-.034)	(1.42)	.62	–	–
731004	12.18 - 13	72	141	.873	175	30	–	–	–	–	–	–	–	–	(.11)	-.020	(-.039)	(.83)	1.34	–	–
	13 - 14	44	125	.719	216	19	–	–	–	–	–	–	–	–	(.11)	-.022	(-.017)	(1.00)	.76	–	–
	14 - 15	12	143	.781	201	14	–	–	–	–	–	–	–	–	(.11)	-.005	(.006)	(.92)	1.02	–	–
	15 - 16	-43	153	.806	104	-1	–	–	–	–	–	–	–	–	(.11)	.015	(.056)	(.90)	2.94	–	–
	16 - 17	-74	106	.666	0	0	–	–	–	–	–	–	–	–	(.11)	.046	(.067)	(1.08)	1.72	–	–
740806	13 - 13.20	286	210	.866	521	26	21	1.79	1.63	1.72	321	179	190	184	.154	-.081	-.054	1.17	.91	.70	.77
	16 - 17	103	93	.541	311	-3	7	1.43	0.85	1.02	179	125	164	150	.152	-.119	-.038	1.84	1.09	.84	.77
	17 - 18	58	89	.493	(200)	-6	-13	0.47	0.00	0.15	88	145	213	185	.108	-.089	-.029	1.44	.67	.93	1.39
	18 - 19	59	6	.434	72	(1)	-18	0.33	-1.14	-0.63	22	68	-643	243	.117	-.133	-.020	1.77	.46	13.98	30.39
	19 - 20	-17	13	.198	-49	-20	-35	-0.78	-3.72	-2.60	50	-64	5	9	.091	.004	.106	3.01	2.41	4.08	1.69
740807	11 - 12	287	182	.569	526	47	69	2.24	2.15	2.17	316	141	145	144	.123	-.288	-.076	1.42	.53	.38	.72
	12 - 13	278	152	.625	527	37	56	1.98	1.68	1.74	313	158	176	172	.116	-.211	-.091	1.22	.64	.60	.94
	13 - 14	242	166	.678	510	26	63	1.41	1.47	1.45	262	185	181	182	.088	-.144	-.131	.85	.66	.69	1.05
	14 - 14.40	204	151	.668	(450)	15	28	1.79	1.53	1.60	271	151	167	162	.088	-.126	-.166	.86	.99	.75	.76
740808	9.44 - 10.07	119	93	(.4)	473	56	51	1.87	1.47	1.40	275	147	171	176	.072	(-.345)	-.223	1.18	.90	.63	.70
	18.20 - 19.10	3	13	.167	17	(1)	-27	-0.20	-1.30	-0.95	-11	55	-147	880	.057	-.095	.062	2.24	3.29	3.07	.98
740809	11.07 - 11.40	51	71	.145	352	48	26	1.76	0.09	0.15	208	118	299	283	(.058)	-3.025	(-.159)	2.62	.36	.15	.42
740820	11 - 12	106	138	.234	461	42	26	0.91	0.71	0.75	207	228	254	249	(.060)	-1.521	(-.206)	1.68	.38	.33	.87
	12 - 13	143	99	.204	470	33	27	1.06	(-0.98)	(-0.13)	228	215	22000	509	(.078)	-3.090	(-.177)	2.51	.36	.49	1.36
	13 - 13.30	134	150	.192	510	25	22	1.54	(-2.64)	(-1.78)	296	192	-298	-626	(.054)	-3.456	(-.322)	1.85	.32	.18	.56
740821	11.10 - 12	53	135	.463	272	25	34	0.44	0.49	0.49	73	165	160	160	.094	-.098	-.031	1.33	.55	.49	.89
	12 - 13	43	93	.378	244	17	31	0.25	0.33	0.32	43	170	160	161	.066	-.147	-.046	1.15	.41	.78	1.90
	13 - 14	51	99	.322	258	13	13	0.37	0.45	0.43	66	179	169	171	.051	-.278	-.129	1.04	.50	.70	1.40
	14 - 15	117	118	.380	323	10	14	1.19	0.76	0.81	168	141	176	171	.035	-.390	-.494	.60	.46	.39	.85
	15 - 15.20	34	97	.324	164	3	20	1.19	0.56	0.64	78	66	92	88	.075	-.181	-.107	1.52	1.37	.40	.29
740822	11.13 - 12	179	125	.456	514	46	–	1.58	1.11	1.18	287	181	222	215	.056	-.347	-.858	.81	.48	.44	.92
	12 - 13	89	175	.546	305	21	–	0.50	0.50	0.50	95	189	189	189	(.097)	-.100	-.043	1.17	.58	.60	1.03
	13 - 14	97	158	.454	263	13	–	0.50	0.44	0.45	83	167	174	172	(.086)	-.188	-.027	1.24	.22	.28	1.22
	14 - 15	102	160	.419	350	11	25	0.75	0.47	0.53	139	186	221	212	(.055)	-.254	-.178	.86	.52	.44	.85
	15 - 15.20	40	117	.337	169	9	7	0.53	0.18	0.23	59	103	137	132	.086	-.190	-.199	.51	.87	.17	.63

Figure 3. Comparison of sensible heat flux values measured by the Bowen ratio method and the eddy correlation method. See runs of table 7.

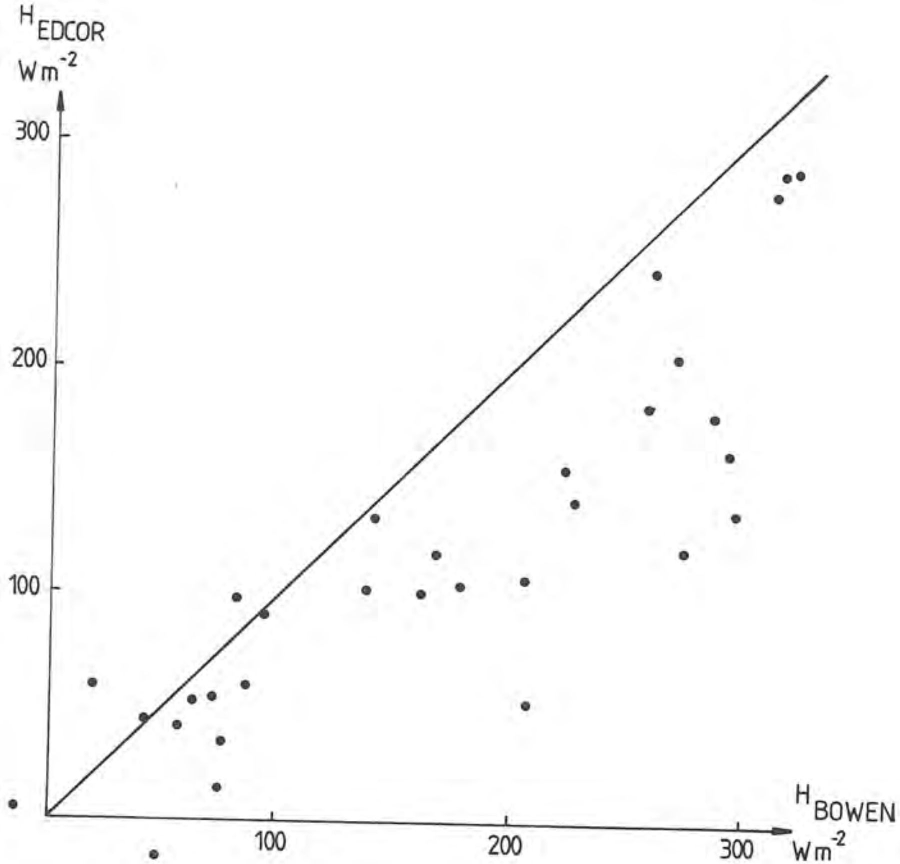
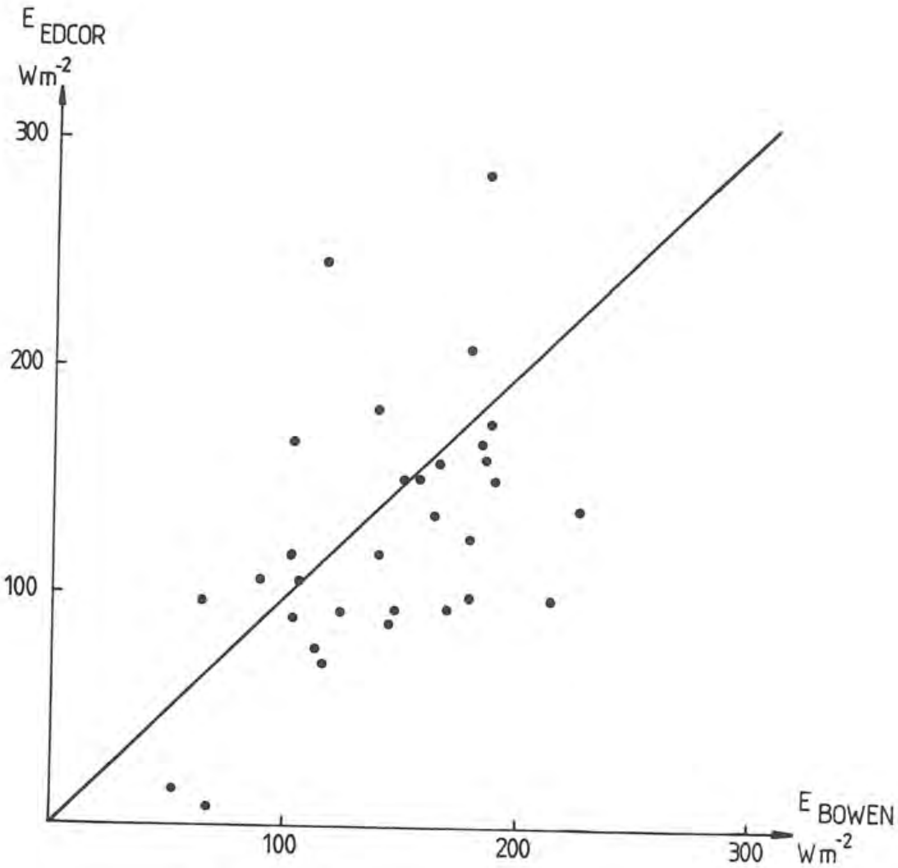
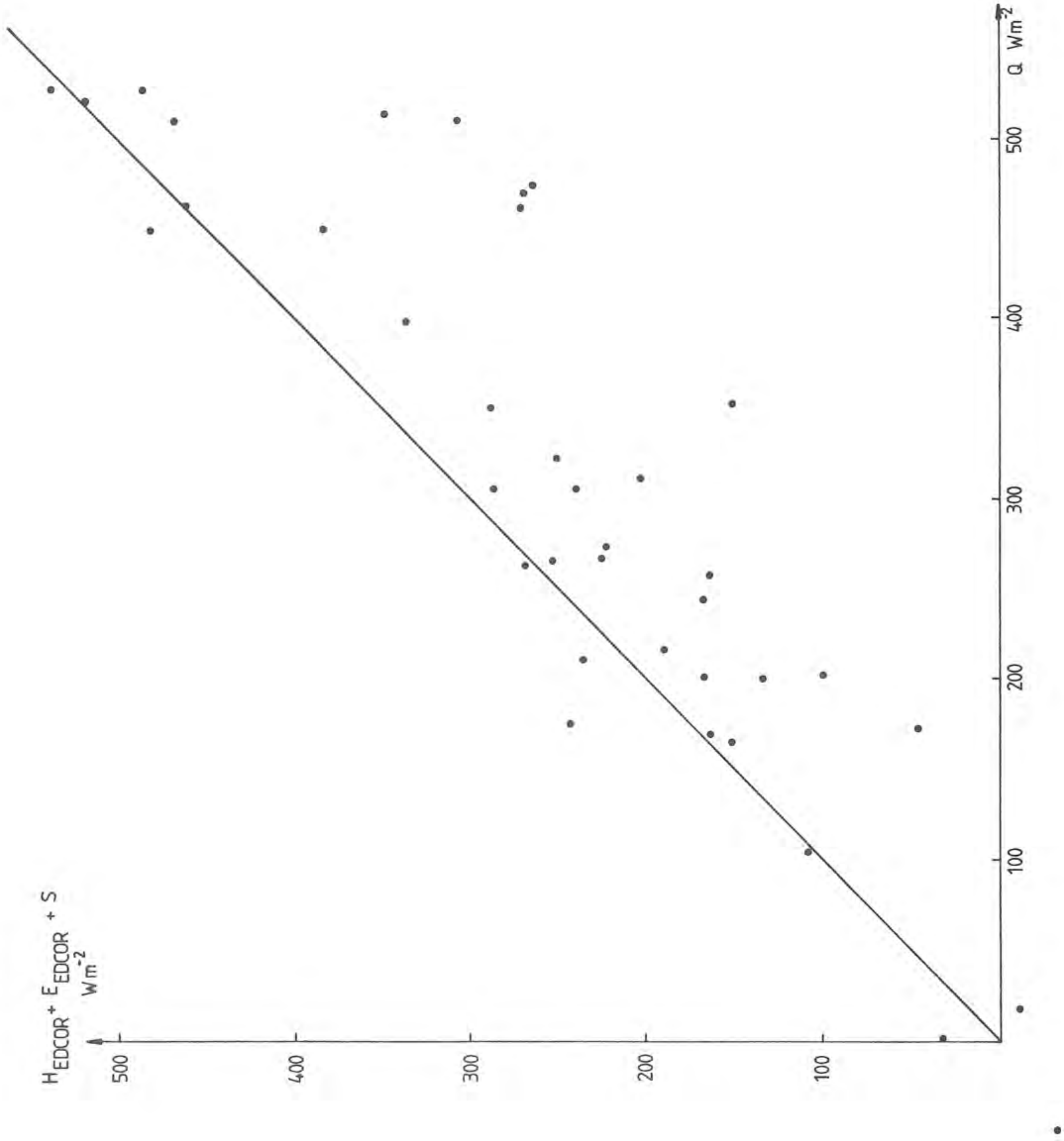


Figure 4. Comparison of latent heat flux values measured by the Bowen ratio method and the eddy correlation method. See runs of table 7.



<u>Figure 2</u>. Sum of eddy correlation fluxes of sensible heat and latent heat plus the flux to heat storage plotted against the net radiation above the Velen forest for the runs of table 7.



Comparison of Bowen ratio method and pan method. Use of pan data to complement the daily Bowen ratio method data. Errors.

It is known from e.g. ref. No 6 that the evaporation rate from a wet forest canopy may be in the average of the order of three times as large as the rate of transpiration from the dry canopy.

To investigate this in relation to Bowen ratio and pan data the days of 1973 and 1974 were divided in three groups:

1. Dry day but rain in the past.

   There is no rain or less than 2 mm in the daytime of day 0. However, there must have fallen

   10 mm or more in day -2 and/or

   5 mm or more in day -1 and/or

   2 mm or more in the night hours between day -1 and day 0.

2. Rainy day.

   There is 2 mm or more in the daytime of day 0. Rain or not in the past.

3. Dry day and dry in the past.

   No rain occurs according to 1 or 2.

To separate the three groups of days the rainfall record from a clearing close to the meteorological mast was used.

For this evaporation comparison the data of table 2 without brackets were used. These 133 values have been obtained by the Bowen ratio method for the days with adequate mast data. Table 3 gives the daily evaporation data from the pan GGI 3 000.

In figure 5 data from groups 1 and 3 are compared. Both groups consist of dry days. The curves have been obtained by the least square method using a third degree polynomial. To assume a relationship of such a high degree is justified since the pan can be expected to give enhanced evaporation values in high radiation days due to strong heating of the water.

It is found that dry days with rain at some earlier time (group 1) have the largest Bowen ratio evaporation. Thus for a pan evaporation of 2 mm the days with rain in the past days (group 1) have a mean Bowen ratio evaporation of 3.4 mm, whence the days with dry preceding days and nights evaporate only 2.7 mm. This must be ascribed to interception on the forest canopy and also evaporation contribution of wet soil and increased soil water after a rainfall.

This comparison was used to estimate the Bowen ratio evaporation in days with missing mast data. For such days the appropriate curve was entered with the value from GGI 3 000 and the expected Bowen ratio evaporation was read. These values are given within brackets in table 2.

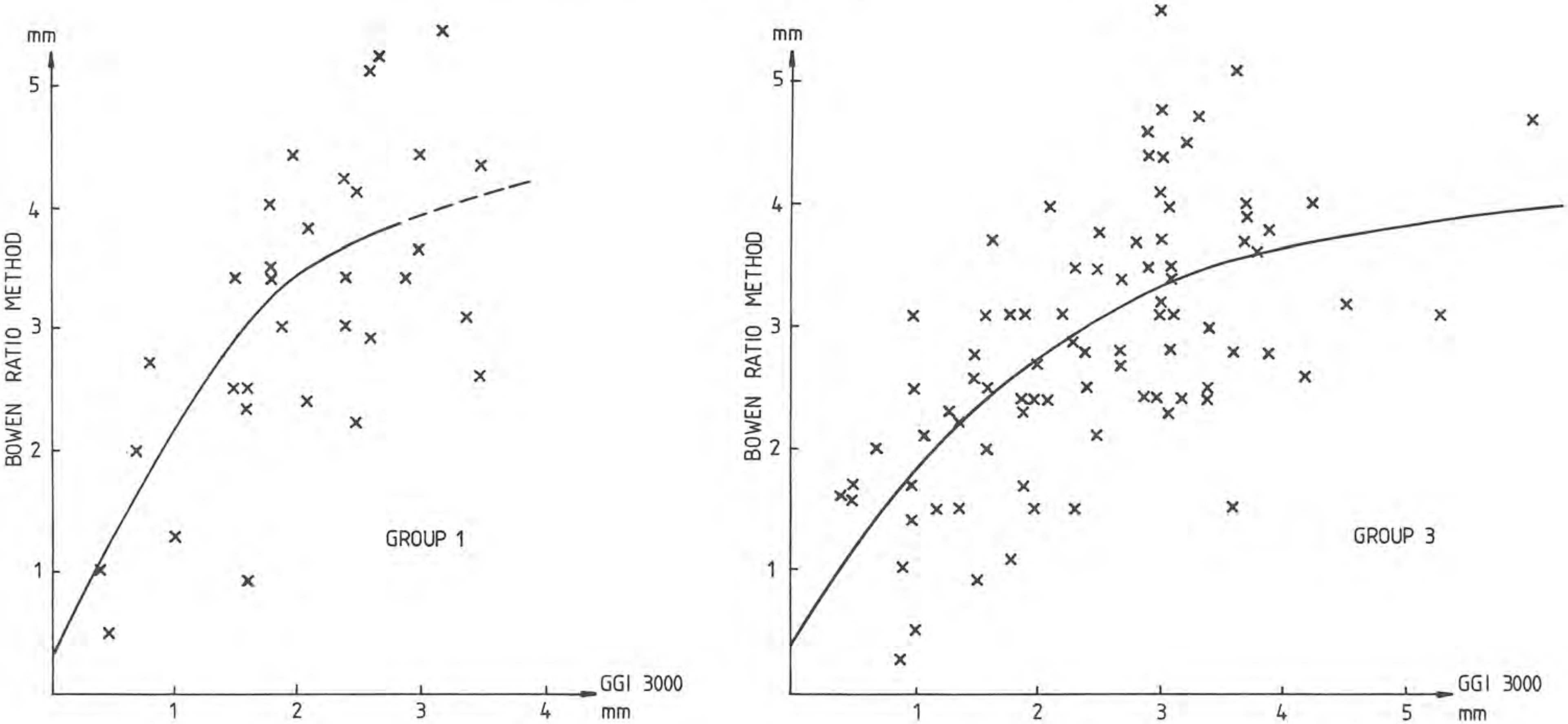


Figure 5. Daily values of forest evaporation by the Bowen ratio method compared to values from the pan GGI 3 000. Group 1 consists of data from dry days but with rain in the past. Group 3 includes dry days with no rain in the past. See the text for details.

The error dE for days with Bowen ratio estimate (days without brackets in table 2) has been computed assuming that for each hour the errors in the input variables (net radiation Q, heat storage G, vertical differences in potential temperature $\Delta\Theta$ and water vapour Δe) are independent of each other. This was achieved using the formula (ref. 1, p 20)

$$dE = \sqrt{\left(\frac{\partial E}{\partial Q}\, dQ\right)^2 + \left(\frac{\partial E}{\partial G}\, dG\right)^2 + \left(\frac{\partial E}{\partial \Delta\Theta}\, d\Delta\Theta\right)^2 + \left(\frac{\partial E}{\partial \Delta e}\, d\Delta e\right)^2}$$

on an hourly basis. We have used dQ/Q = 10%, dG/G = 20%, $d\Delta\Theta$ (between hights 16 m and 29 m above ground) = 0.03°C and $d\Delta e$ = 0.05 mb.

dE has been summed in parallel with E to form a total error for the whole day.

In table 2 the errors have been summed also into monthly values without regarding the possibility that the error may be positive one day and negative the next. Probably there is some reason for making this pessimistic assumption, since e.g. net radiation may have the same sign of its error for long periods. The error for days with missing mast data (days with brackets in table 2, see method using pan data described above) will of course be larger. This error was estimated by plotting dE against E for days with Bowen ratio data. The values of dE for the days without Bowen ratio data were taken to be close to the largest occuring error for each given E value.

Comparison of Bowen ratio method and water balance method. Use of trough method. Discussion.

In figure 6 and 7 the monthly water balance data are summarized. The monthly sums by the Bowen ratio method have been taken from table 2. The water balance and rainfall sums arise from table 4 and refer to the whole Velen basin. The data for the pan GGI 3 000 are taken from table 3. The interception data have been taken from the interception study carried out in the forest surrounding the mast, with monthly data in table 6.

In June - August of 1973 and 1974 evaporation calculated by either method: Bowen ratio (Bo), Water balance (Wb) and pan GGI 3 000 exceeds the rainfall. As can be seen in table 4 this depends on the decreasing lake, soil and subsoil storages during the summer.

The monthly Bo-values are larger than those of the pan. Then one could be tempted to conclude that the Bo-values are in error and too large.

However, the evaporation of rain intercepted on the canopy is included in the Bo - and Wb-values but not in the pan values. If the interception is subtracted the pure forest transpiration is obtained, see table 8.

Table 8. Monthly estimates of pure forest transpiration and comparison with the pan data.

	Bo total	Wb total (Velen area)	Inter- ception I	Bo transp.	Wb transp.	Pan GGI 3 000
1973						
May	-	62	-			59
June	-	81	8		73	99
July	114	95	16	98	79	92
Aug	104	93	21	83	72	79
Sept	72	60	20	52	40	51
1974						
May	107	56	7	100	49	101
June	100	74	17	83	57	96
July	89	87	19	70	68	79
Aug	81	63	17	64	46	69
Sept	51	-	27	24		36

From this table it may be seen that the Bo-values reduced by interception are of the same magnitude as the pan values and that the reduced water balance values are smaller.

It must be pointed out that the pan values cannot be regarded as potential transpiration from forest and thus not as an upper limit for the forest transpiration. The potential forest transpiration has to be regarded as the transpiration from the dry canopy when the root zone has field capacity of water. This amount can never be simulated by a pan or a purely meteorological formula since the biological nature of the forest is involved and especially its surface resistance (bulk stomatal resistance). This resistance regulates the transpiration and it depends on meteorological conditions but also on the species, leaf area index, age of the forest and the time of the season. (see section II and III of this report.) Thus, from a comparison with the pan data alone it cannot be concluded that the Bo-values are too large.

In September of both years the lower evaporation is due entirely to reduced transpiration. The interception loss is the same or larger than in the summer months and its part of the total evaporation is much higher.

The monthly Bowen ratio evaporation values are larger than those of the water balance method. This is so for all the months studied but especially marked for May and June of 1974. Possible reasons for the difference between the methods were discussed for August 1974 in ref. No 1. Here this discussion will be repeated and somewhat complemented.

1. The Velen area was covered by forest to only 66%. If the area had been covered by forest to 100% the water balance method would have given larger evaporation since more of the rainfall over the catchment would have been lost by interception. Then there would probably have been better agreement with the Bowen ratio data which are valid for the forest area around the mast. By using the amounts intercepted for the months studied and the water balance data for the entire Velen area (66% forest) and the sub basin Nolsjön (84% forest) separately, table 9 is obtained.

Table 9. Evaporation data from the water balance method and estimated possible values if there had been 100% forest. Comparison with the Bowen ratio method.

	Evaporation (mm) from the Velen area (66% forest) by water balance method	Possible evaporation if the whole Velen area had been covered by forest	Evaporation from the Nolsjön area (84% forest) by water balance method	Possible evaporation if the whole Nolsjön area had been covered by forest	Bowen ratio method with error interval
1973					
May	62	-	70		
June	81	84	76	77	
July	95	100	88	91	114 ± 29
Aug	93	99	100	103	104 ± 27
Sept	60	67	56	59	72 ± 25
1974					
May	56	59	66	67	107 ± 29
June	74	79	76	79	100 ± 33
July	87	94	83	86	89 ± 28
Aug	63	67	65	68	81 ± 21
Sept	-		-	-	51 ± 17

This improves the agreement somewhat but most of the Wb-values are still smaller especially for May and June of 1974. Here and maybe also in general other reasons have to be sought.

2. It is known that forests have low albedo. Assuming that the albedo is 25% in the non-forested areas and that the range 7 - 12% measured from the Velen mast (see ref. No 5) is valid for the forest areas which take 66% of the Velen basin, it is estimated that the reduction in the Bowen ratio evaporation will be 4%. But such an estimate should include other values of the Bowen ratio over the non-forest area.

The two effects of 1 and 2 cannot be added.

The following factors may make the evaporation values by the Bowen ratio method too large. They may have some part in the excess found in comparison with the water balance method. The factors have also been discussed in ref. No 1 and will be just mentioned here:

- Local sampling and calibration errors due to e.g. light reflexion from the mast
- Systematic error in the rate of heat storage
- Errors in the differences in vapour pressure and temperature
- The site may be improper so that advection effects may occur
- The effect of dew formation may give an overestimate in only counting the dew evaporation and not the condensation. This was estimated however to give only 3 mm for August 1974.

Some of these errors have been included in the error calculus discussed above and error limits given in the tables.

At last there has been made a study of the largest monthly values which are theoretically possible to get by the water balance method. These values are shown in table 10 for the Nolsjön sub-basin. They have been calculated using the highest observed rainfall sums out of 5 or 6 adjoining rain gauges and also the soil water tube giving the largest changes in soil water amount. However it is not considered to be especially probable that the soil water tube in question gives changes which represent area values for the forest.

Table 10. Comparison of evaporation obtained with the Bowen ratio method with the water balance method — in the Nolsjön sub-basin — and the largest theoretically possible values.

	Evaporation from Nolsjön area by water balance method	Theoretically possible maximum value (see the text)	Bowen ratio method with error interval
1973			
May	70	98	
June	76	86	
July	88	107	114 ± 29
Aug	100	121	104 ± 27
Sept	56	-	72 ± 25
1974			
May	66	77	107 ± 29
June	76	98	100 ± 33
July	83	115	89 ± 28
Aug	65	80	81 ± 21
Sept	-	-	51 ± 17

<u>Figure 6</u>. Year 1973. Monthly values of total forest evaporation obtained by the Bowen ratio method and the water balance method. The evaporation from a GGI 3 000 pan is also shown. We also give the monthly rainfall and the part intercepted on the forest canopy and evaporated. The figures given are numbers of days which had high quality mast data used for the Bowen ratio estimate.

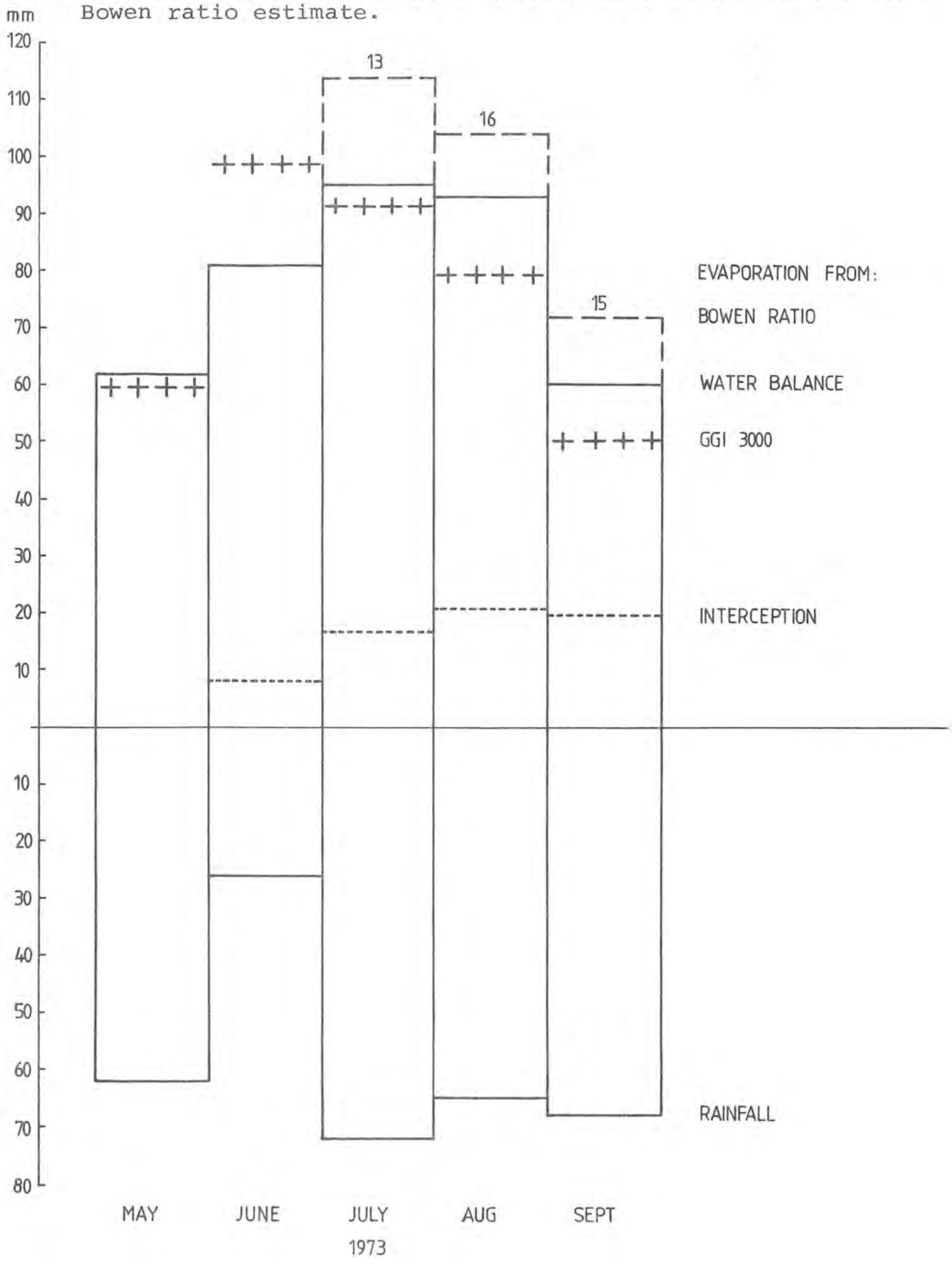
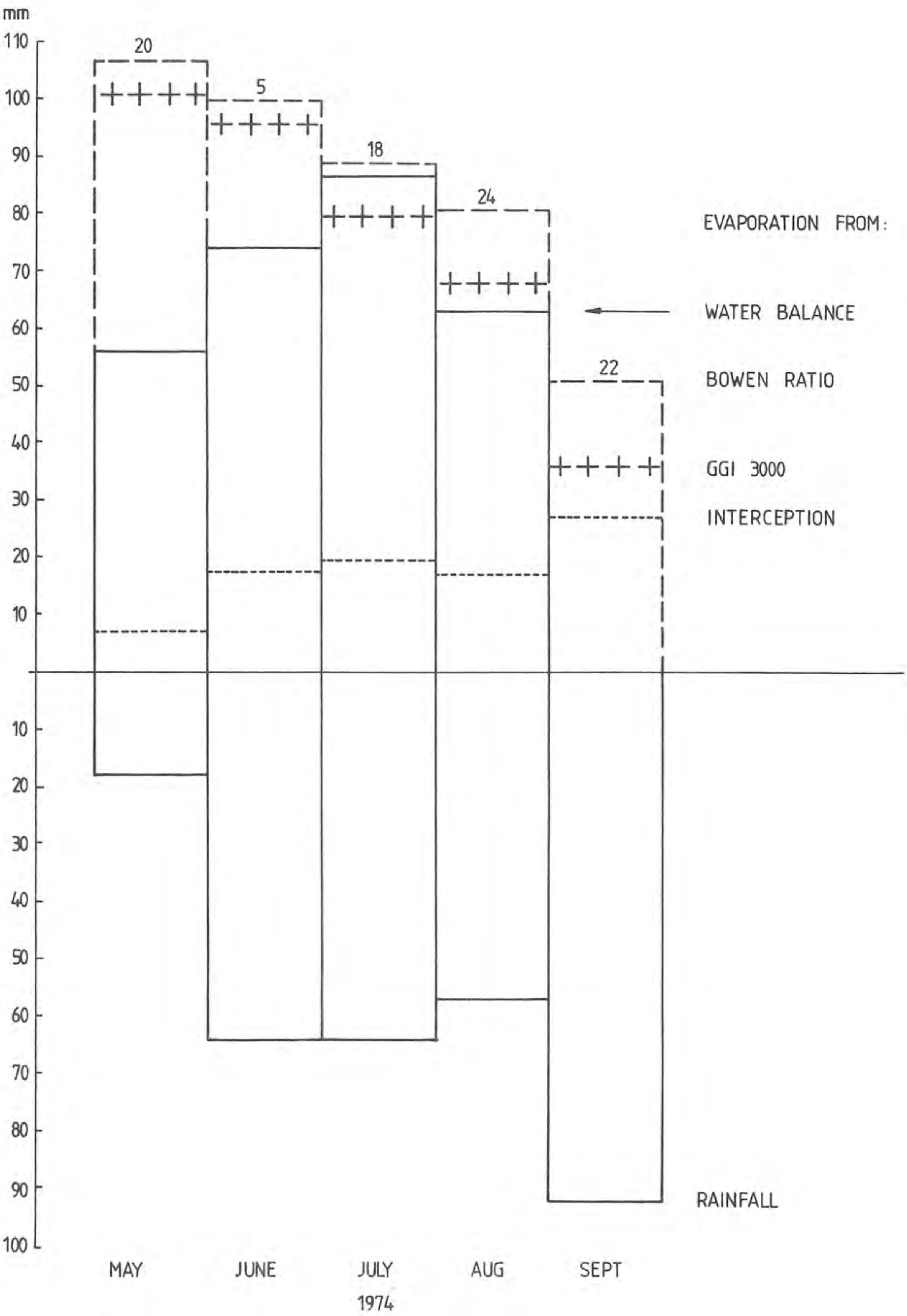


Figure 7. Year 1974. Explanation, se figure 6.



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II PRACTICAL DETERMINATION OF EVAPORATION FROM FOREST. RECOMMENDATION ON REQUEST BY THE NORDIC HYDROLOGICAL COMMITTEES, JANUARY 1980

Introduction

For hydrological purposes monthly evaporation values are required. However the evaporation measurement often must be made with a higher time resolution.

If for a forest you know detailed values and variations of some basic properties and if you have a mathematical model (in the simplest case a formula) where these properties appear, then you may calculate the evaporation daily and hourly. You can also state how it depends on some easily measured variables such as meteorological data. See a. below.

The most important basic properties in the simple model to be discussed under a. are the surface resistance and the water storage capacity of the forest canopy. The surface resistance depends on several factors characteristic for each canopy such as species, age, leaf area index (LAI) valid for the season of the year but also on environmental variables such as insolation, soil moisture and the saturation vapour pressure deficit (v.p.d.) of the air.

If the evaporation from a forest will be studied it should be pointed out that at present it is not possible to deduce from the literature relevant values of the basic properties with variations in time and space. Literature data exist for some forests but the necessary data on age and LAI plus the dependence of the surface resistance on the environmental variables mentioned have not been presented in a systematic and uniform way. Thus, in most forests one has to start a vaste program in order to measure evaporation directly during say three years time, see b. below. From these results the basic properties should be determined and presented.

The goal is that you will only need to make simple measurements in each new forest and then use method a. In order to achieve this you have to measure evaporation by more complete and direct methods according to b. Then you have to put together the values of the basic properties and the necessary background data from several different forests in a systematic way.

a. The values of the basic properties are known

An example on a model of the kind mentioned in the introduction is the following:

If you measure v.p.d., net radiation and wind above the canopy and also take a continuous rainfall record in a clearing close to the forest, then the evaporation for say a month may be calculated from a summation of hourly values with the Penman Monteith formula:

$$\sum E = \sum_t \frac{\Delta(Q-G) + \rho c_p \dfrac{e_s(T) - e}{r_a}}{\Delta + \gamma\ (1 + \dfrac{r_s}{r_a})} \approx$$

$$\approx \sum_{t_d} \frac{\rho c_p}{\gamma} \frac{e_s(T) - e}{r_s} + \sum_{t_w} \frac{\Delta(Q-G) + \rho c_p \dfrac{e_s(T) - e}{r_a}}{\Delta + \gamma}$$

where t_d is the number of hours with dry canopy and t_w the number of hours with wet canopy. t_w and the aerodynamical resistance r_a are fundamental but their values are difficult to establish. Therefore an expression has to be used, which gives the interception loss (the last term above) as a function of the rainfall and its time distribution. This expression contains the storage capacity for rainwater of the canopy.

It is also possible to compute evaporation on a daily basis. Then r_s-values have to be deduced which are valid (weighted) to hold for a night and day.

As mentioned above the basic properties and their variation are fundamental and these models can only be used when you are sure that the basic properties are well-known enough.

As an example the following measuring program may be mentioned:

Make hourly measurements and computations. The hourly values are summed into weekly and monthly values. The following variables are measured:

1. At one height a meter or so above the top of the canopy:

   - saturation vapour pressure deficit (from temperature and humidity)

   - net radiation

   - wind speed and direction

If it is not possible to measure at this height, v.p.d. and wind speed should be recorded in an open and well-ventilated place at 2 meters above ground and shortwave incoming radiation should be measured at a place with free horizon.

2. In an open place close to the forest such as a clearing the rainfall should be recorded with a time-resolution of one hour or shorter.

3. Free rainfall and throughfall should be measured in an open place and below the canopy during one season. Weekly values are sufficient.

4. The soil water content should be measured, see below.

b. The values of the basic properties are not known

The methods for direct measurement of evaporation from a forest canopy are summarized in the following table:

Method	Basic measurements	Typical time constant for the sensors	Typical averaging period	Remarks
1. Bowen ratio method	Above the canopy: Net radiation and vertical profiles of humidity and temperature	10 minutes for fixed sensors Mobile sensors for vertical profile must have 1 minute or less	1 hour	Gives total evapotranspiration
2. Eddy correlation method	Above the canopy: Rapid fluctuations of humidity and vertical wind velocity	0.1 second	1 hour	Gives total evapotranspiration
3. Water balance method	Rainfall Runoff Changes in storages of soil water, subsoil water, lake water and snow	-	1 month	Gives total evapotranspiration
4. Interception measurements	Total rainfall Throughfall Time distribution of rainfall. Periods with wet and dry canopy respectively	- - 1 hour -	1 week - " - - -	Gives evaporation of intercepted rain water only
5. Physiological measurements	Transpiration from needle or leaf (single or groups) Measurements of leaf area index (LAI)	-	-	Gives transpiration only

As many as possible of these methods should be used concurrently. One should use a data sampling system which allows one to get data immediately after the measurement in raw and processed form.

When measuring forest evaporation concurrently by two or more methods, these methods will often give different results, and it may be extremely difficult to learn to know why. Therefore all measurements should be made with rigorous checks of measuring site and instruments and the positioning of the sensors. Furthermore, within each method one should make additional measurements in order to get answers concering e.g. the total water and energy balance. Examples, see below.

Comments to the methods above

The micrometeorological methods 1 and 2 may give difficulties depending on sloping on complicated terrain and on the so called oasis effect. The latter will easily occur if a forest smaller than 1 - 2 kilometers is surrounded by farmland. Then it may be preferable to divide the measuring data material in groups according to wind direction. Therefore, the micrometeorological methods should be complemented by a wind direction record.

The necessary data checking needs a quick access to processed data and this may be solved by micro processor techniques.

1. Bowen ratio method

Over forest vertical gradients of the order of 0.01^{o}C in temperature and 0.01 mb in water vapour pressure per meter may be important and this demands extremeley great care in measuring and using the Bowen ratio method. Temperature and humidity in principle must be measured at two heights over the canopy. Regarding possible shortcomings of the measuring site and instrumental errors one should prefer to take data at several heights up to some 15 meters over the top of the canopy and within the canopy. Profiles at low height above the canopy are the most easy to use. Firstly the gradients are larger here and secondly the requirements are smaller on the length upwind of uniform forest stand (the fetch) see (1).

Attempts to estimate the error of the Bowen ratio method due to instrument inaccuracy and positioning have been made in section I in this report.

When using the Bowen ratio method the energy fluxes to storage in the forest stand, soil and air have to be subtracted from the net radiation. These fluxes have to be estimated or may be measured directly (1).

It should be pointed out that the exchange coefficients for heat and water vapour are not necessarily equal over forest. However equality is normally assumed when using the Bowen ratio method. This gives cause also for using the eddy correlation method over forest.

Within not too dense forest stands the ground and its low vegetation contribute significantly to the evaporation. It is very difficult to evaluate the vegetation layers which are sources and sinks for sensible and latent heat. The Bowen ratio method is one-dimensional and fails if there is horizontal convergence or divergence of water vapour. This is often so within forest stands, see (1), and alternative methods such as lysimeter measurements should be considered to determine the evaporation from the soil and the low vegetation.

2. Eddy correlation method

It is difficult to record the rapid humidity fluctuations continuously. In this case one has to take records of not more than a few hours duration and under continuous attention.

Also, one should record concurrently the fluctuations of temperature and horizontal wind velocity in order to get the vertical sensible heat flux and the momentum flux respectively.

If only the variations of vertical and horizontal wind plus temperature are recorded it may be easier to achieve a long continuous record. Then the evaporation flux may be roughly estimated by subtracting the heat flux from the net radiation flux.

3. Water balance method

The water balance method may give the total evaporation by a much smaller data material (monthly values) than the micrometeorological methods (secondly to hourly values). The accuracy of the evaporation values increases with the length of the period studied. The accuracy also depends on the relative magnitude of the measuring values of rainfall, runoff and storage change to be used.

In principle the total evaporation is obtained only if the free rainfall is measured, that is at an open place close to or in the forest (clearing). Several rain gauges around the forest area (within some kilometer) are to be prefered.

In some locations it is possible to define clearly a runoff area and there all the terms in the water balance equation have to be measured. In other areas the runoff is negligible and it may suffice to measure only rainfall and storage changes.

4. Interception measurements

Interception data should be taken at all programs. In computing evapotranspiration from a forest, special techniques must be used for evaporation of intercepted rain water. The length of the periods when the canopy is wet is of vital interest to know for a given time interval and can be indicated by several wetness sensors (1).

The free rainfall should be measured in some open places, see 3 above. The values of throughfall must be well representative for the stand and this can be achieved by using several evenly spaced rain gauges with large catchment area under the canopy. See e.g. (4) where also the error has been estimated.

In interception studies in a deciduous forest the stemflow may be important and has to be measured (2).

5. Physiological measurements

Physiological measurements are fundamental since the transpiration from a forest is directed by its stomata. In order to obtain surface resistance values representative for the whole canopy, data from individual needles or leaves have to be combined with tha LAI, (1). The LAI may be estimated for a stand but varies with the time of the season also for a coniferous forest.

As was seen in the introduction the values of resistances and other basic properties found in the literature have not been put together systematically. Therefore is needed background information and comparisons between the methods described above. Investigations with concurrent measurements using methods 1, 3, 4, 5 or 1, 4, 5 are examples.

For reference purposes it is necessary to make a complete forest inventory for each stand to be studied.

Winter conditions

Generally the difficulties in measurement are very large in the winter. However, the transpiration is very small from both coniferous and deciduous forests.The only method which has been used to some extent is the water balance method. Here, the measurement of snowfall is very difficult.

Soil water measurements

The surface resistance depends on the soil water potential (soil water content), see (3) and these variables should be measured, especially in direct studies under b., see (1).

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III ACTUAL EVAPORATION FROM FOREST (CONTRIBUTION TO IHP-SEMINAR IN COPENHAGEN IN NOVEMBER 1979)

Direct measurement

(At first the Bowen ratio and eddy correlation methods were discussed. This will be deleted here since these methods were discussed in II above).

Aerodynamical profile method

Comparison of evaporation flux data over forest between the aerodynamical profile method and the eddy correlation method shows (5) that the exchange coefficients for heat and water vapour, K_H and K_E respectively are about twice as large as expected from traditional formulae. However, these results depend strongly on what value used for the zero-plane displacement, d. It has been found extremely uncertain to determine numerically the parameters u_*, z_o and d in the logarithmic wind profile (13). Due to these facts the aerodynamical method can not yet be regarded as an independent method.

The Penman-Monteith formula and simplification for forest

The Penman-Monteith formula is fundamental for estimates of real evaporation, deduction and discussion, see (6):

$$\lambda E = \frac{\Delta(Q-G) + \rho c_p \dfrac{e_s(T) - e}{r_a}}{\Delta + \gamma \quad (1 + \dfrac{r_s}{r_a})} \qquad \text{(A)}$$

In (7) is found a discussion of the four factors of importance (available energy Q - G, saturation vapour pressure deficit $e_s(T) - e$, aerodynamical resistance r_a and the surface resistance of the stand r_s).

The chances of use the formula depend on what is known about the values of r_s and r_a. The formula has the practical advantage that meteorological data are needed from <u>one</u> height only.

The widely used Penman equation is a special case where r_s has been put equal to zero. This has been considered to give the so called potential transpiration. However $r_s = 0$ will not give the potential transpiration (defined to take place from dry vegetation with good supply of water in the root zone) but the evaporation from a wet canopy. As has been shown (8) the evaporation from a wet forest, in the average, may be three times as intensive as the transpiration from the dry forest in the same overhead conditions. The reason for the fact that the Penman formula has yet given reasonable estimates for forest is that booth its numerator and denominator have been too small. Revision of the Penman formula has been discussed in (9).

For dry forest r_s/r_a is of the order of 30. A typical value for r_s is 100 sm^{-1} and for r_a 3 sm^{-1}. Here the atmosphere allows for an effective removal of the vapour due to the strong turbulence and so r_a is small. Therefore, the forest itself has to slow down the transpiration and this is made by the surface resistance r_s. The v.p.d. acts as the driving force (10). These facts are illustrated simply by the fact that for dry forest the Penman-Monteith formula can be approximated by

$$E \approx \text{konstant} \cdot \frac{e_s(T) - e}{r_s} \tag{B}$$

That this is so has been shown by measurements which verify that the second term in the numerator of (A) (the ventilation term) is typically about 5 times as large as the first (the energy term). In the denominator $\gamma\frac{r_s}{r_a}$ dominates and so r_a can be reduced and (B) is obtained.

Interception of rain water

The most widely used method to measure the interception loss is by placing rain gauges at the side of and under the canopy (11). Of additional methods described may be meantioned measuring the bending of water - loaded branches and measuring the attenuation of a gamma radiation beam directed horizontally through a canopy (12).

The interception loss in a Swedish conferous forest (Velen area) in two summer periods has been found to be about 70 mm or some 1/4 of the rainfall (11), (13). The most important factors affecting this share is the storage capacity of rain water (2 mm for the Velen area) and the time distribution of precipitation. If a rainfall amount is distributed in short showers the interception loss will be largest.

From measurements in the Thetford forest (UK) important conclusions were drawn in (8) for wet and dry canopies.

The rate of evaporation of intercepted rain water (in mm/hr) may be considered to be proportional to the water amount covering the forest (15).

The rate of evaporation during a rainfall has been estimated to be 10% of the rainfall rate itself (14).

These findings show, that separate methods must be used to estimate the evaporation of intercepted rain water, before the total evapotranspiration from a forest is calculated.

The use of resistances in the Penman-Monteith equation

The formula may be used to determine r_s directly from measurements in a dry forest. The most important data to be taken then are transpiration flux, v.p.d. and net radiation. r_a has to be calculated by the aerodynamical profile method. As was seen above this method is very uncertain over forest. However this is not serious for dry forest, since the value of r_s is insensitive to r_a when using the Penman-Montheith formula (16). This has to do with the fact that this formula can be approximated by (B) above.

Using the fact that r_s is near zero for a wet canopy, there has been discussed a method to take into consideration the evaporation of intercepted water in calculating the effective surface resistance for a longer period, say a month (9).

The surface resistance r_s of the stand may be regarded as an auxiliary parameter in practical calculations. As was shown in (17) there is a relation between the surface resistance, the resistance of a unit area of a needle or leaf and the leaf area index, LAI. The latter resistance has also been measured directly by porometer (17). In some studies good agreement has been found between the surface resistance of the stand computed by the Bowen ratio technique and estimates using porometerdata and the LAI. The surface resistance of a forest canopy is generally found to increase during the day and this depends on successive closing of the stomata openings. It has been found that the typical daily resistance values depend on incoming radiation, v.p.d. and soil water potential.

If the dependence of r_s and r_a on various factors is surveyed then the Penman-Monteith formula may be used to compute the evaporation for periods and forests where no direct measurements have been made. Then it will also be possible to predict the consequences of various measures such as cutting.

Of the references (6) and (19) the first deals with general principles and the second describes and compares some micrometeorological and physiological computer models.

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IV GENERAL CONCLUSIONS AND PLANNING THE COMPLETION OF THE PROJECT

The project "Development of methods to determine actual evaporation from weather data" will be finished with a report to appear in 1981, where values of the surface resistance will be presented. In the present report 133 daily evaporation values calculated by the Bowen ratio method were presented, but no corresponding resistance values. One goal of the present report was to see if there were any sign, that the 133 values were systematically too large or too small.

The evaporation in the summers of 1973 and 1974 calculated by the Bowen ratio method was found to be in the average some 25% larger then that obtained by the water balance method. The former values were also larger then those of the pan GGI 3 000. However, due to reasons described above it cannot be concluded that the Bowen ratio method gave too large evaporation values. Thus, for the calculation of resistance values (using the Penman-Monteith equation), the 133 daily evaporation values presented above are planned to be used. Therefore, the value $K_H/K_E = 1$ will not be changed.

However, there will be some discussion how the surface resistance values (r_s) will be presented and what environmental data will be added. A statistical comparison of r_s with the environmental data will be made.

In all these studies uniformity with the work on other data sets has to be aimed at, so that multi-project reviews will be possible to make in the future. (See also section II above.) To achieve that, discussions will be taken up with other groups.

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