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Ecole Nationale des Ingénieurs des
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METHODS FOR CALCULATION OF ACTUAL AND POTENTIAL EVAPOTRANSPIRATION

Application to Hupselse Beek Catchment (The Netherlands) 1983-84

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METHODS FOR CALCULATION OF

ACTUAL AND POTENTIAL EVAPOTRANSPIRATION

Application to 'Hupselse Beek' catchment area
The Netherlands, 1983-1984

Dominique Chatillon

'Mémoire présenté en vue de l'obtention du diplôme
d'ingénieurs des techniques de l'équipement rural'

This work, realized for the third study year of the rural engineering school ENITRTS (Ecole Nationale des Ingénieurs des Travaux Ruraux et des Techniques Sanitaires), Strasbourg, France, was done in the Department of hydraulics and catchment hydrology of the Agricultural University, Wageningen, The Netherlands, within the frame of the development of the relationships between high schools in the European Community.

'All rivers flow to the sea,
nevertheless the sea never becomes full'

Ecclesiaste 1:7

ACKNOWLEDGEMENTS:
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I want here to express my gratitude to all the people who are working in 'De Nieuwlanden'.They welcome me very well and it was always a great pleasure but also an enrichment for me to talk with them.

Particular thanks to Han Stricker,my supervisor in this work,whose help and advices have been invaluable.Acknowledgements to Piet Warmerdam,the director of the department,Paul Torfs and Jacque Kole who helped me a lot with handling the data and with the work on computers, to Anton Dommerholt who made the cover and to Anne-Marie for her help in typing.

SUMMARY:
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In the East of the Netherlands,an experimental catchment,'the Hupselse Beek catchment ' is managed by various organizations.A meteorological station provides data which can be used for the calculations of the evapotranspiration.Main landuse in the catchment is grassland.

As well for the estimation of actual evapotranspiration as for estimation of potential evapotranspiration,several methods are reviewed.
For the actual evapotranspiration,three methods, based on the measurements of wind velocity and temperature profiles and on the energy balance are studied.The theoretical background is the similarity theory of turbulent transport of Monin and Obukhov.The theory establishes the likeness of the turbulent transport for sensible heat,momentum and latent heat.The advection-aridity method,proposed by Brutsaert and Stricker (1979) ,as a conceptual method to estimate actual evapotranspiration is employed during the growing season and more particularly for dry periods.
Potential evapotranspiration is computed by four methods,according to the formulations of Penman,Thom and Oliver,Priestley and Taylor and Makkink.

With respect to the estimation of actual evapotranspiration,the method based on the use of the energy balance and the sensible heat flux, calculated from the profiles,is the most convenient to implement and yields more reliable results.The two other methods based on the theory are more difficult to apply instrumentally (wet-bulb temperature) and need more accuracy.As far as the results from the Bowen ratio method are acceptable (results underestimated of about six percents),the results from the direct method are too low (sometimes up to fifty percents) and too scattered.

During a dry period,the advection-aridity method ,which requires the meteorological data used for the calculation of the potential evapotranspiration as input data,can,according to the employed formula lead to good results.

Among the formulations used for estimation of the potential evapotranspiration,the one developped by Thom and Oliver yields results which appear to be in best agreement with the actual evapotranspiration outside the dry periods.The water budget calculated with these values is very well balanced.

RESUME:
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METHODES POUR LE CALCUL DE L'EVAPOTRANSPIRATION REELLE ET POTENTIELLE:

Application au bassin 'Hupselse Beek ',Pays-Bas,1983-1984.

Il existe dans l'Est des Pays-Bas,un bassin expérimental géré par diverses organisations.Il est équipé d'une station méteorologique qui fournit des données servant au calcul de l'évapotranspiration. L'herbe constitue la principale utilisation du sol.

Plusieurs méthodes sont examinées,tant pour l'évapotranspiration réelle que pour l'évapotranspiration potentielle.
Pour l'évapotranspiration réelle,trois méthodes,basées sur les mesures de profiles de vitesse du vent et de température,et sur le bilan énergétique sont étudiées.Elles s'appuient sur la théorie des similarités des transports des flux de chaleur sensible et de chaleur latente et de la quantité de mouvement.La méthode dite 'advection-aridité' proposée par Brutsaert et Stricker (1979),comme une méthode conceptuelle pour estimer l'évapotranspiration réelle,est utilisée durant la période de croissance des plantes et plus particulièrement pour les périodes sèches.
L'évapotranspiration potentielle est calculée par quatre méthodes,selon les formules de Penman,Thom et Oliver,Priestley et Taylor et Makkink.

Tout en respectant la valeur de l'estimation de l'évapotranspiration réelle,la méthode basée sur le bilan énergétique et sur le flux de chaleur sensible,calculé à partir des profiles,est la plus pratique à mettre en oeuvre et fournit de bons résultats.Les deux autres méthodes fondées sur la même théorie sont plus difficiles à installer et demandent une plus grande précision des mesures.Les résultats obtenus par la méthode du rapport de Bowen sont acceptables (sous-estimés de six pour-cent par rapport à la méthode du budget énergétique),mais ceux dérivés de la méthode de calcul direct par les profiles sont trop faibles(parfois inférieurs de moitié) et trop dispersés.

Pendant une période sèche,la méthode d'advection-aridité,qui requiert les données météorologiques utilisées dans le calcul de l'évapotranspiration potentielle comme valeurs d'entrée,peut,selon la formule employée,donner de bons resultats.

Des quatre formules employées pour estimer l'évapotranspiration potentielle,celle de Thom et Oliver semble fournir les valeurs qui sont les mieux ajustées aux autres composantes du bilan hydrique.

TABLE OF CONTENTS:
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SYMBOLS , NOTATIONS , CONVERSION FACTORS :

These symbols are used throughout this report.Some symbols which are of a local importance are defined where they are introduced.

Cp	:specific heat at constant pressure	(J/kg/K)
D	:discharge	(m^3/s;mm/day)
do	:displacement height	(m)
e	:water vapour pressure	(mbar)
es	:saturation vapour pressure	(mbar)
E	:actual evapotranspiration:general meaning or calculated by the direct method	(W/m^2)
EB	:evapotranspiration calculated from the Bowen ratio	(W/m^2)
EH	:evapotranspiration calculated from the sensible heat flux and the energy budget equation(indirect method)	(W/m^2)
Ep	:potential evapotranspiration	(w/m^2)
ETA1 ETA2 ETA3	:actual evapotranspiration calculated by the advection- :aridity method (1st,2nd or 3rd formula) :	(W/m^2)
ETM1 ETM2	:potential evapotranspiration calulated by Makkink's :formulations	(W/m^2)
ETPE	:potential evapotranspiration calculated by Penman's formula	(W/m^2)
ETPT	:potential evapotranspiration calculated by the formula of Priestley and Taylor	(W/m^2)
ETTO	:potential evapotranspiration calculated by the formula of Thom and Oliver	(W/m^2)
G	:soil heat flux	(W/m^2)
H	:Sensible heat flux	(W/m^2)
k	:Von Karman's constant	(-)
L	:Monin-Obukhov's stability length	(m)
Le	:latent heat of vaporization	(J/kg)
P	:precipitation	(mm/day)

q	:specific humidity	(-)
qs	:saturation specific humidity	(-)
r	:coefficient of correlation	(-)
ra	:aerodynamic resistance	(s/m)
rc	:canopy resistance	(s/m)
Rg	:global radiation(short-wave radiation incoming)	(W/m^2)
Rh	:relative humidity	(-)
Ri	:Richardson number	(-)
Rn	:net radiation	(W/m^2)
Rso	:short-wave radiation outgoing	(W/m^2)
s	:slope of the saturation vapour pressure curve($s=\delta qs/\delta T$)	$(mbar/^0K)$
T	:temperature	(^0K)
Td	:dry-bulb temperature	(^0K)
Tw	:wet-bulb temperature	(^0K)
u	:wind velocity	(m/s)
u*	:friction velocity	(m/s)
z	:height	(m)
zoh	:roughness length for heat	(m)
zom	:roughness length for momentum	(m)
zov	:roughness length for vapour	(m)
β	:Bowen ratio (H/E)	(-)
γ	:psychrometric constant	$(mbar/^0K)$
ρ	:density of the air	(kg/m^3)
Θ	:potential temperature	(^0K)
θ	:soil moisture content	(-)
θ_s	:saturation soil moisture content	(-)
τ	:shear stress at the surface	$(kg/m,s^2)$

A $^-$ above the name of a variable means that the mean value is taken.

Σ symbolyses a sum and Δ or δ a difference.

Conversion factors:

-Evapotranspiration:

$1\ W/m^2 = 1\ J/s,m^2$

Le ,the latent heat of vaporization is at about 288 K,$2.46.10^6$ J/kg.

So 1 W/m^2 enables the vaporization of $\frac{1}{2.46.10} = 4.06.10^{-7}\ kg/s,m^2$,or or $3.51.10^{-2}\ kg/day,m^2$.

$1\ kg/m^2 = \frac{1dm^3}{1m^2} = 1mm.$

Then $1\ W/m^2 = 4.06.10^{-7}\ kg/s,m^2 = 3.51.10^{-2}\ mm/day$

-Discharge:

$1\ m^3/s = 86.4.10^3\ m^3/day.$

The surface of the watershed is $6.5.10^6\ m^2$.So $1m^3/s = \frac{86.4.10^3}{6.5.10^6}\ m/day$

Then $1\ m^3/s = 13.3\ mm/day.$

CHAPTER 1 : INTRODUCTION

Water is an essential factor for life.But as this vital element covers about three-quarters of the earth's surface,only less than one percent of the total volume is fresh water,available for drink-water supply or for industrial or agricultural use.In the developped countries,the amount of water which is used up is always increasing, whereas more and more resources are affected by pollution.Human activities and particularly the changes as the intensification of agriculture,the changes in land use,urbanisation and industrialisation are also of great influence.In the developping countries,both problems:quantity and quality are crucial.

More and more hydrological studies are thus required:theoretical research,to get the best knowledge and understanding as possible of the processes,and studies,applied to a watershed,in order to define the hydrological characteristics,necessary to a rational use of water.

The evapotranspiration is one of the four components of the hydrological balance.Maybe because of the theoretical background,maybe because it requires accurate and numerous measurements,the evapotranspiration is probably the least studied in the hydrological aspects.

The department of hydraulics and catchment hydrology of the Agricultural University in Wageningen is involved in the management of an experimental catchment,the 'Hupselse Beek catchment'.A meteorological station provide data,which can be used for the calculations of the evapotranspiration.

Various theories are studied and then used to compute potential and actual evpotranspiration,here from the data measured in 1983 and 1984.An analysis is then made to establish the accuracy of the different methods and the relationships existing among them.The calculation of the water balance enables to make a link with the other components of the water balance.

CHAPTER 2: THE HUPSELSE BEEK CATCHMENT AREA

The data which had been analysed in this study come from a meteorological station located in the experimental catchment Hupselse Beek.

2.1.Brief history:

The Hupselse Beek project started in 1968 and it was presented as a contribution to the international hydrological decade in 1968. The management is carried out by the study group Hupselse Beek with representatives from the State Public Works(water management service),from the department of the Water Management of the Province of Gelderland and from the departments of water management and of hydraulics and catchment hydrology of the Agricultural University of Wageningen.

The main objectives of the study group are:

- investigation of various hydrological processes in the area: relationships between rainfall and runoff, between meteorological variables and actual evapotranspiration ,modelling of groundwater flow, effect of field drainage on the hydrological regime.
- examination of the advantages and use of existing and new research techniques.
- testing existing and newly developed observational equipments.
- field work for students.

Four main items of research are based on this experimental catchment:

-Observation of the rainfall-runoff modelling:
The first aim of this study is to determine the dischargeable or effective part of the rainfall for short time intervals.
The second aim is the creation of a model simulating the hydrograph of the outflow. Observations of surface runoff from temporarily waterlogged surfaces and of rapid runoff from the tiledrain flow have been done.From these measurements,Warmerdam(1980)assumed that the hydrograph of the outflow from the Hupselse Beek catchment consists of two flow components:

- a fast reacting component with contributions from surface runoff.
- a slow reacting component,induced by groundwater flow.

The result of this work is the 'Wageningen model',used to fit continuously the calculated and observed outflow rates for,in this case,three-hours intervals.

-Evapotranspiration:
Evapotranspiration data are of interest for the knowledge and modelling of the soil-water-plant system,for the water balance and the calculation of the excess rainfall as a result of the rainfall-runoff model.

Several methods are used to calculate actual and potential evapotranspiration and it is the object of this study to use them for analysing the data of 1983 and 1984.

-Soil variability:
Soil properties vary in space,even in soils which are seemingly uniform or or within a soil map unit.
Some data already available were independently determined:rainfall,discharge,storage changes evapotranspiration and groundwater.In order to use them in numerical models, other data were required and a research program started in 1981.In 1981-1982,soil surveys were done (1300 borings) and in 1983-1984,21 sites were analysed for soil physical data.These data were used for the study of soil physical variability and water transport in the unsaturated soil.

A project of the European Community started at the end of 1987 and its objective is the study of spatial variability of land surface processes. Several universities and institutes within Europe cooperate in this international project.

-Solute transport:
This program started in 1985.Nowadays,agriculture is applying more and more nutrients which results in a contamination of the groundwater used for drink-water supply,especially in sandy regions.
Parametric models for testing the solute transport are developped and the Hupselse catchment constitutes a very attractive area for field-scale experiments,because the shallow aquifer has a very short turnover time (couple of years).

3.2.The area:

The alluvial catchment area of the Hupselse Beek is situated in the east of The Netherlands,in the province of Gelderland,between the villages of Groenlo and Eibergen and the Dutch-German border.Map 2.1 shows the situation of the catchment in the Netherlands.

In contrast with the flat low-lying polders in the western part of the country,this region is well above the sea level.The altitude varies between 33m and 24m at the outlet. The general slope of the land is from east to west with an average of 0.008.

It is the upstream sub-area of the Leerinkbeek catchment area that discharges into the river Berkel near the village of Borculo.The river Berkel is a tributary of the river Ijssel which is a delta branche of the Rhine. In the catchment, the rivulet Hupsele Beek flows through a wide valley with a relatively steep slope of 0.0025 to 0.0055. Fixed weirs at several places in the rivulets controls the flow against too high velocities.

The catchment area is 6.5km2. Land use is mainly agriculture,about 70% of the land is covered with grass,20% is arable land and 6% is covered with woods.

MAP 2.1:THE NETHERLANDS (Scale 1/2.150.000)

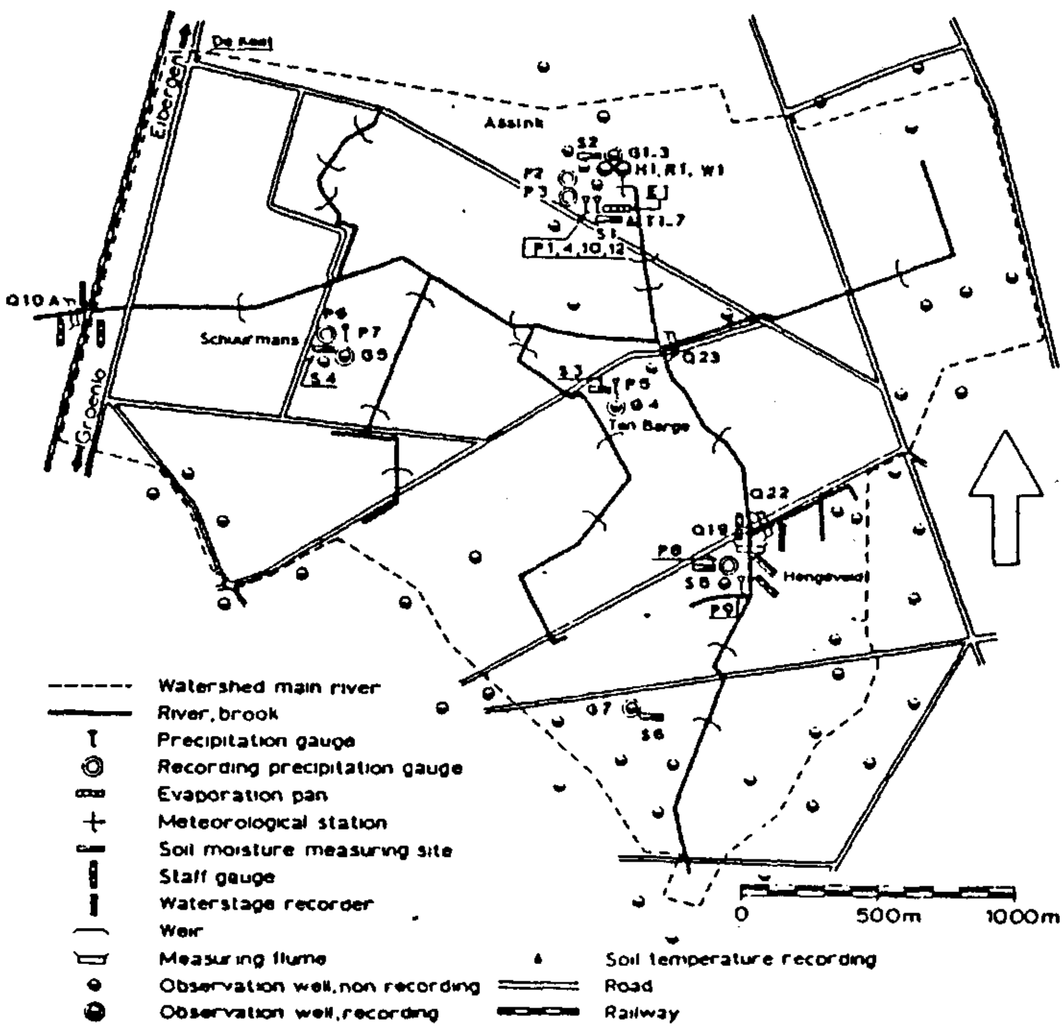
The upper part of the soil consists of sand deposits ,which are lying on a thick tertiary formation of marine clays. The thickness of the sand aquifer varies between 1m and 8m from east to west.Consequently, the transmissivity and the storage capacity of the soil are relatively small.The groundwater table is shallow,about 50cm below the ground surface in winter whereas in summer it may decline to about 1.30m to 2.00m.

3.3.The measurements:

3.3.1.The program of measurements:

During the first eight years,the measurements were concentrated on rainfall and runoff. But after some dry years,it was decided to take more interest in the meteorological network for calculating actual and potential evapotranspiration. This resulted in the installation of equipment to measure net radiation and temperature profiles in the soil as well as in the boundary layer.The data collection system became automated at that time.

The measurements are done in different sites(See map 2.2).



MAP 2.2.:Hydrometeorological network of the Hupsel area (From Warmerdam)

The most important site is the meteorological station in Assink where the following data are collected:

-short-wave radiation incoming (Rg) and outgoing (Rso)
-net radiation (Rn)
-soil heat flux (G)
-sun duration (SD)
-rainfall(P)
-temperature profiles:
-temperature difference between 1.30m and 3.15m above the soil surface (D13)
-temperature at 3.15m above the soil surface (D3)
-temperature difference between 7.14m and 3.15m above the soil surface (D73)
-surface temperature(Ts)

The measurements were done by using psychrometers at three levels,each containing two temperature sensors.One sensor measured the dry-bulb temperature,another one measured either wet-bulb temperature during three periods in 1983 and 1984(from the 23th of June at 14h00 to 30th of June at 12h00 and from the 13th of July at 11h00 to the 20th of July at 12h20 in 1983 and from the 23rd of August at 13h00 to the 11th of September at 00h00 in 1984) or otherwise also the dry-bulb temperature.These data are related as D13,D3,W13 for the first serie and W13,W3,W73 for the second.

-wind profile:
-wind velocity difference between 2.14m and 3.97m above the soil surface(CT2)
-wind velocity at 3.97m above the soil surface(CT3)
-wind velocity difference between 9.48m and 3.97m above the soil surface(CT3)
-wind direction(WD)
-relative humidity(RH)

These data provide the possibility to calculate actual evapotranspiration indirectly from the sensible heat flux and the energy balance.

Soil moisture is measured at six sites. It allows in principle the calculation of the soil water storage.

With this set of measurements,the components of the water balance and of the energy balance are measured independently.

Other sites for measuring groundwater table,water levels and flows in the rivulets are scattered over the catchment area.

Table 2.1 gives the information concerning the data (components, measurements, instrumentations, interval ,data collection and number of sites).

3.3.2.Data control and processing:

Some data are kept on punched tapes but most of them are on magnetic tapes. They have to be printed in order to check the quality.After that, it may be decided to repair or to make a new calibration on certain devices,in case of suspicious data.

Table 2.2 is an example of rough data.

TABLE 2.1:Summary of the measuring program,carried out in the
--------- Hupselse Beek (From Warmerdam,Stricker and Kole 1982)

COMPONENT	MEASUREMENT	TYPE OF INSTRUMENTATION	INTERVAL (RANGE)	DATA COLLECTION	NUMBER OF SITES
Soil moisture	neutron probe	N.E.A.	2 weeks	form	6
Runoff	water level	HL-flumes, V-Romijn	15 minutes	punched tape	3
Precipitation	ground level gauges +40-cm level gauges	several recording and non-recording gauges	15 min., 24 hours	cassette tape, form	3
Groundwater	groundwater wells	perforated tubes	15 min, 4 times a year	cassette tape, form	130
Net radiation balance	net radiation global radiation sunshine duration short wave reflection	CSIRO net radiometer Kipp-solarimeter Haenni, Campbell Stokes Kipp-solarimeter	20 min. 20 min. 20 min., hourly 20 min.	cassette tape cassette tape cass. tape, sheet cassette tape	1 1 1 1
Soil heat flux	soil temperature (6 levels) flux plates (3)	Thermistors T.P.D.-Delft	20 min. 20 min.	cassette tape cassette tape	1 1
Sensible heat flux	dry bulb temperature (3 levels) surface temperature wind velocity (3 levels)	Semi-conductors, TFDL Wageningen Heimann-kT16 cup anemometers (K.N.M.I.) Lambrecht	20 min. 20 min. (3 months) 20 min. hourly	cassette tape cassette tape cassette tape graphical chart	1 1 1
Evapotranspiration	wet bulb temperature (3 levels) relative humidity wind direction temperature relative humidity air pressure	semi-conductors, TFDL Wageningen hair hygrometer (Lambrecht) wind vane, Lambrecht wind vane, Lambrecht thermo-hygrobarograph	20 min. (6 months) 20 min. 20 min. hourly hourly	cassette tape cassette tape cassette tape graphical chart graphical chart	1 1 1 1 1

TABLE 2.2:An example of rough data(Between brackets is a serie of 20
--------- values measured at the same time)

0	-13	99999999	0	[1	-55	146	1261
1449	-36	135	41	-36	135	40	-36
21	79	0	1002	0	6	99999999	0]
1	-57	146	1261	1449	-31	133	33
-32	133	31	-39	24	77	0	1007
0	0	99999999	0	1	-57	146	1261
1449	-30	131	32	-29	132	30	-35
24	76	0	1011	0	21	99999999	0
1	-57	146	1261	1448	-28	130	30
-28	131	28	-37	24	79	0	1011
0	6	99999999	0	1	-57	146	1261
1449	-28	128	27	-28	129	25	-38
22	65	0	1015	0	19	99999999	0
1	-55	146	1261	1449	-29	124	27
-29	125	26	-34	20	68	0	1019
0	3	99999999	0	1	-57	146	1261
1450	-19	125	19	-18	126	16	-31
25	65	0	1023	0	10	99999999	0
1	-57	146	1261	1449	-15	123	12
-15	123	10	-30	26	60	0	1027
0	6	99999999	0	1	-54	146	1261
1449	-15	122	15	-15	123	14	-30
24	56	0	1027	0	-5	99999999	0
1	-50	146	1261	1449	-12	121	11
-11	121	10	-24	21	56	0	1031
0	-9	99999999	0	1	-48	146	1261
1449	-12	122	11	-12	122	10	-26
20	59	0	1031	0	2	99999999	0

The devices are calibrated several times a year.The obtained curves are then used to calculate the right values from the rough data. Conversions are also done on the data,e.g. to calculate the wind velocity in cm/sec from values in counts/sec.Incidental corrections are also done. Finally, definite files, usable for calculations can be written and stored on tapes.

The general way of doing this is reported in figure 2.1.

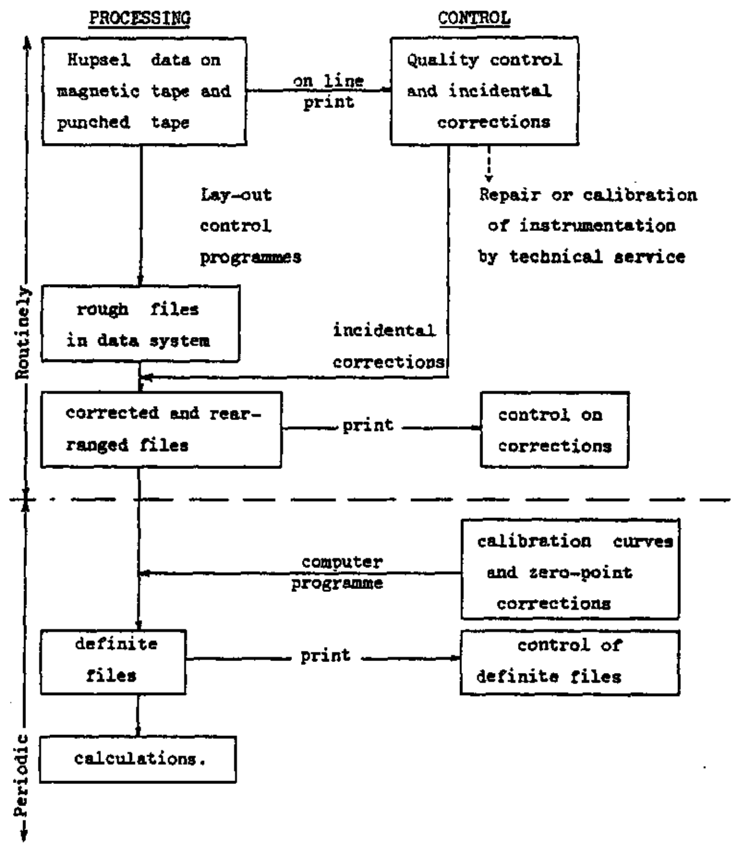


FIGURE 2.1:Scheme of data processing and data control of the
---------- Hupselse Beek(From Warmerdam,Stricker and Kole 1982)

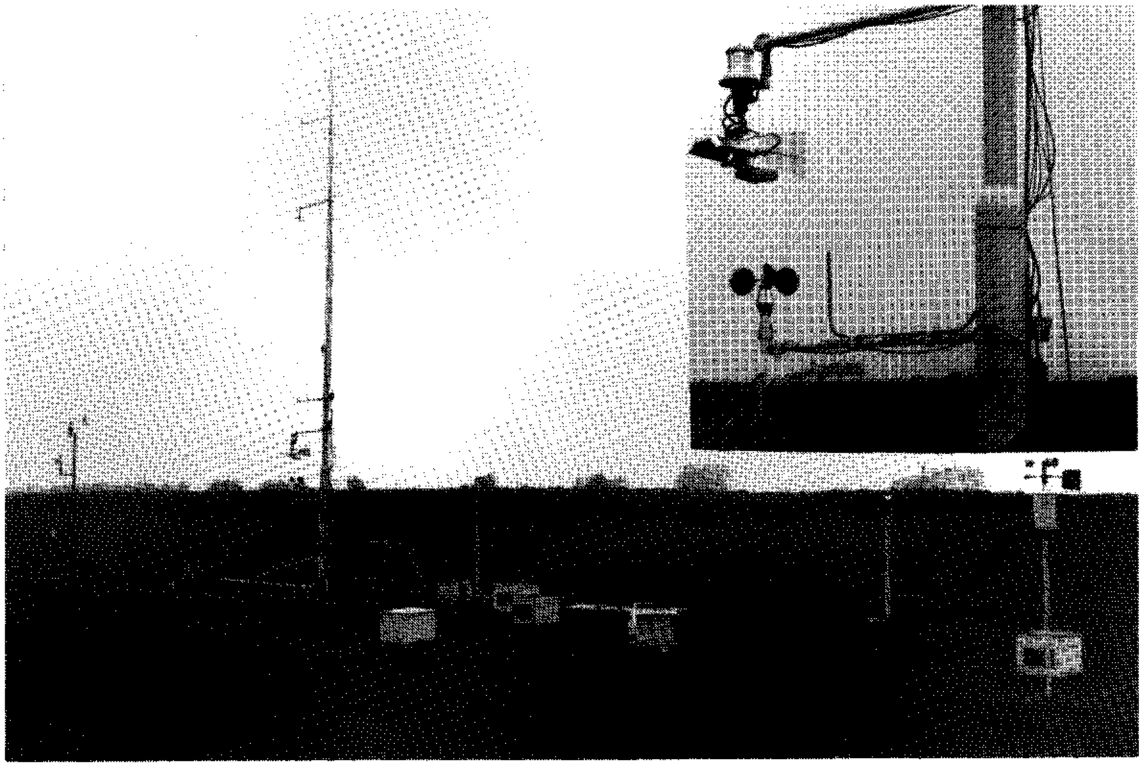
In this study,I analysed the rough data files of the period going from the 1st of January 1983 to the 31st of October 1984.These data were collected on three magnetic tapes. Every 20 minutes,20 data were recorded so that the number of data is 1440 per day and 525600 per year. These large files were not directly usable on a Personal Computer(P.C.).My first work was thus to make them exploitable.That means:

-writing the date and time before each serie of 20 values.
-setting all the dummy values (originally 99999999) to 9999 (same format as the other data)
-making files covering periods of 2 months,which size enables to keep the data on floppy disks usable on a P.C.

Table 2.3 shows the presentation of the data after this arrangement.

TABLE 2.3:The data after corrections and calibration.

Day.time	Rg	Rn	Rain	G1	G2	D13	D3	D73	W13	W3
W73	U2	U3	U9	ST	RH	SD	WD	G	Rso	
831950000	0	-12	0.00	1380	1416	-5	134	2	1	109
-5	218	234	282	133	754	0	354	-9	-2	
831950020	0	-12	0.00	1380	1417	-6	135	3	1	109
-4	223	244	288	133	741	0	336	-9	-2	
831950040	0	-11	0.00	1380	1416	-8	135	3	3	110
-5	210	234	267	134	760	0	327	-9	-2	
831950100	0	-10	0.00	1380	1416	-8	135	4	4	110
-5	209	234	276	136	768	0	331	-9	-2	
831950120	0	-10	0.00	1379	1418	-8	136	5	3	110
-6	244	273	321	136	760	0	331	-9	-2	
831950140	0	-10	0.00	1379	1417	-7	137	2	2	110
-5	242	263	304	135	741	0	345	-8	-2	
831950200	0	-11	0.12	1379	1417	-6	137	2	2	109
-5	242	263	308	133	738	0	336	-8	-2	
831950220	0	-11	0.00	1379	1418	-6	136	2	1	109
-4	269	293	357	135	723	0	363	-8	-2	
831950240	0	-11	0.00	1379	1418	-7	137	3	2	108
-5	222	244	295	133	723	0	370	-8	-2	
831950300	0	-11	0.00	1379	1418	-7	136	3	2	109
-5	193	214	254	137	737	0	340	-8	-2	
831950320	0	-11	0.00	1380	1419	-8	134	4	3	110
-5	185	204	241	133	760	0	334	-8	-2	



The meteorological station Assink

CHAPTER 3:THE MAIN THEORIES

3.1.History*:

Already in the Greek Antiquity,some persons had an idea of the hydrological phenomena.Xenophanes of Colophon (6th century B.C.) wrote:'What happens in the sky is caused by the heat of the sun;when the moisture is drawn up out of the sea,...it forms a cloud and drips out as rain ... and the winds spread it around.'Aristotle(4th century B.C.) thought about the solar radiation as the source of the exhalation ('Moist exhalations requires solar radiation or another source of heat.') but he never imagined a cause and effect relation between wind and evaporation.

During the Roman period the classical greek philosophers theories had a great influence and nothing really new appeared.A lot of writings were about 'Why the level of the sea does not increase?',e.g.Lucretius(1st century B.C.) wrote :'besides the sun by his heat draws off a great portion.'

The Middle Ages are marked by a relapse in the development of physical science.

The 17th and 18th centuries saw the first measurements and experiments.Descartes is one of the first natural philosophers to break away from Aristotle's concepts.'The winds are caused nearly only by the vapours.'.For Descartes,wind is air in motion,caused by the expansion of the vapours rising from the water surfaces,the humid earth,snow and clouds, and it is more the result of the evaporation than the cause.

Perrault made the first experiments on evaporation during a cold winter (1669-1670).He reported 'Having exposed seven pounds of frozen water to the cold air,found them diminished in eigtheen days by nearly one pound'. So he found two more causes for the evaporation:cold and the movement of particles in the air.

Franklin (1757) reported from several observations that 'wetting the thermometer with spirits brought the mercury down by five or six degrees'. That leads to the discovery of the latent heat.

Van Musschenbroek (1769) explained the effects of the wind:first the wind takes the vapours away and the second effect appears especially when it is dry,because the wind contains a large amount of electricity and enhances the separation of the particles.

The foundations of the present theories are in the 19th century.The starting point is Dalton's paper in 1802.He presented his views on gaz mixtures and a table of the saturated vapour pressure as a function of the temperature.

*:Main sources :Brutsaert 1982.

Dalton's results translated in present-day notations are:

$$E = fD(u).(es^{*}-ea) \quad (3.1) \quad \text{(Brutsaert 1982)}$$

where E is the rate of evaporation (height of water per time unit)
fD(u) is a function of the mean wind speed
es* is the saturation vapour pressure at the temperature of the surface
ea is the vapour pressure in the air.

Later, several relations were proposed (Soldner 1804, Stelling 1882).

3.2. The theories used for the calculation of the actual evapotranspiration and based on temperature and wind profiles:

3.2.1. Introduction: the water cycle:

A permanent water flow is established at the surface of the earth: the water cycle (or hydrological cycle). From the oceans, water evaporates, raises into the atmosphere and after a condensation in small drops, forms clouds. When the saturated air masses becomes colder, the vapour condenses and water returns to the oceans or to the earth as precipitation.

Partly the precipitation infiltrates or is discharged directly as overland flow or evaporates and goes back to the atmosphere.

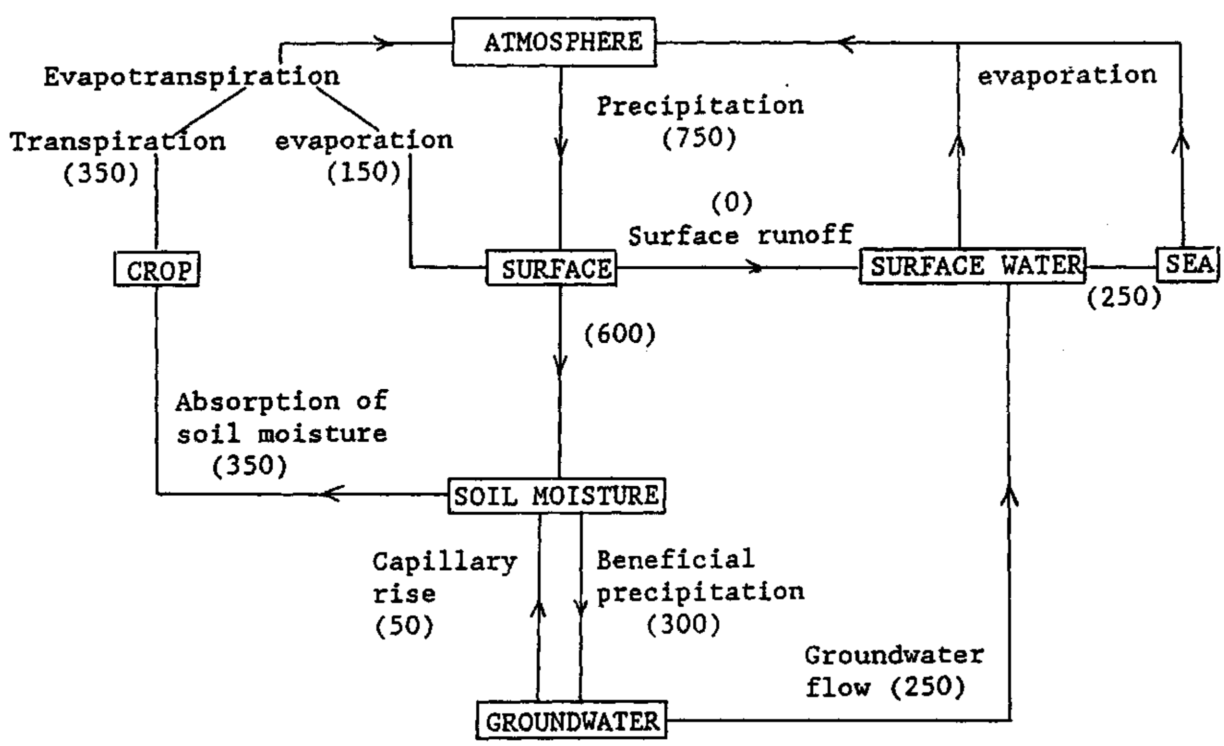


FIGURE 3.1: Watercycle of a cultivated land
(750): amount in mm/year in the Netherlands (order of magnitude)
(From van der Molen 1983)

The energy which maintains the water masses in motion is the solar energy.The starting point of the water cycle is thus the evaporation which is in the first place a thermic phenomenon.Heat exchanges between the atmosphere,the soil surface and the oceans are the motor of the evaporation.They are keeping the water cycle up.

The horizontal plane of exchange, which must be regarded with the largest attention in the study of evaporation ,is considered at the earth surface.

3.2.2.The energy balance:

The energy budget at the soil surface has been established by De Vries (1963)

$$Rn + H + E + G = 0 \qquad (3.2)$$

Rn:net radiation
H:sensible heat flux
E:latent heat flux
G:soil heat flux

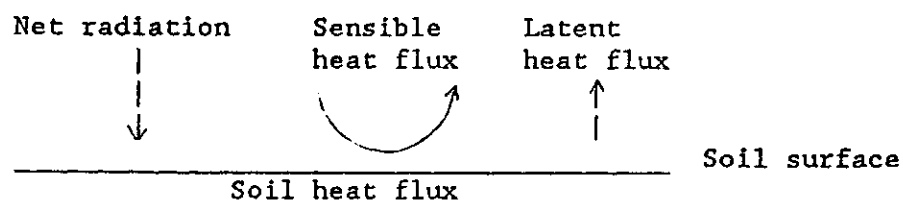


FIGURE 3.2:The energy balance at the surface of the earth

The different terms represent the energy fluxes per unit of time.The terms which are an input for the surface are counted positively and those which are a loss negatively.

The net radiation is the resultant of four components:

-The short-wave radiation incoming (often called global radiation):Rg
-The short-wave radiation outgoing:Rso

These short-wave radiations are solar radiations.The sun behaves like a full radiator with a surface temperature of about $^{0}6000$ K. Most of the radiation emitted at this temperature is confined to the waveband from 0.3 to 3 μm.(Monteith 1973).The radiations which reach the earth are short-wave radiations.These radiations are partly reflected by the soil (Short-wave radiation outgoing)

-The long-wave radiation incoming:
It is the atmospheric radiation. The solid and liquid particles and the

gazes of the atmosphere absorb a part of the solar radiation and emit this energy as a long-wave radiation (infra-red) .The atmospheric radiation depends on the quantity of carbone dioxide and of water vapour in the atmosphere.It is partly absorbed by the soil.

-The long-wave radiation outgoing:Rlo

The soil heated by the sun emits long-wave radiation(from 4 to 100μm) (Tardy 1986)This radiation can be calculated by the Stefan's law:

$$Rlo = \epsilon_S \cdot \tau \cdot T_S^4 \qquad (3.3)$$

where T_S is the soil's surface temperature in k

ϵ_S is the emissivity of the surface

τ is the Stefan-Boltzmann constant: 5.67 10^{-8} W/m²/K

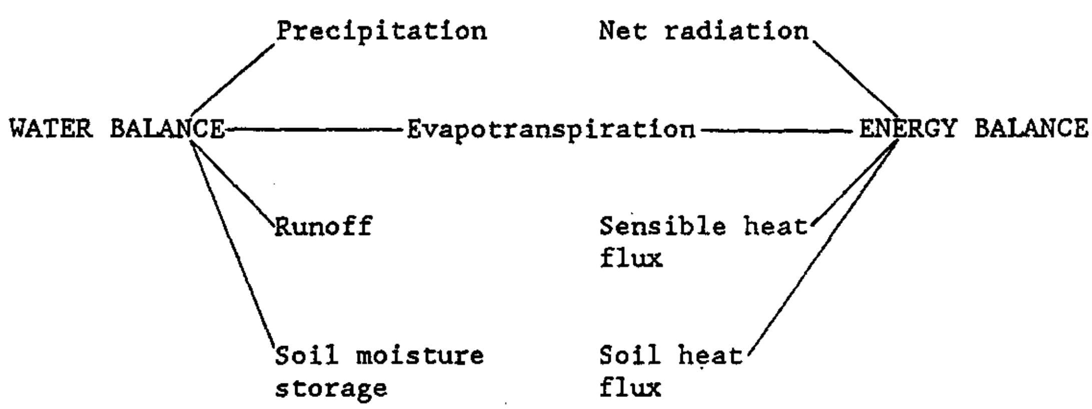
The sensible heat flux is the heat flux exchanged by convection.It depends on turbulent motion in the atmospheric surface layer.It is a function of temperature,humidity and wind speed,at the surface and at a certain altitude.

The latent heat flux or evapotranspiration is the result of any condensation which occurs at the soil surface if there is no accumulation of water vapour on the soil.

The soil heat flux is a heat flux exchanged by conduction in the soil.

Figure 3.3 shows the evolution of the four components of the energy balance during a summer day (10/08/1983)

The evapotranspiration makes the link between the energy balance and the water balance.



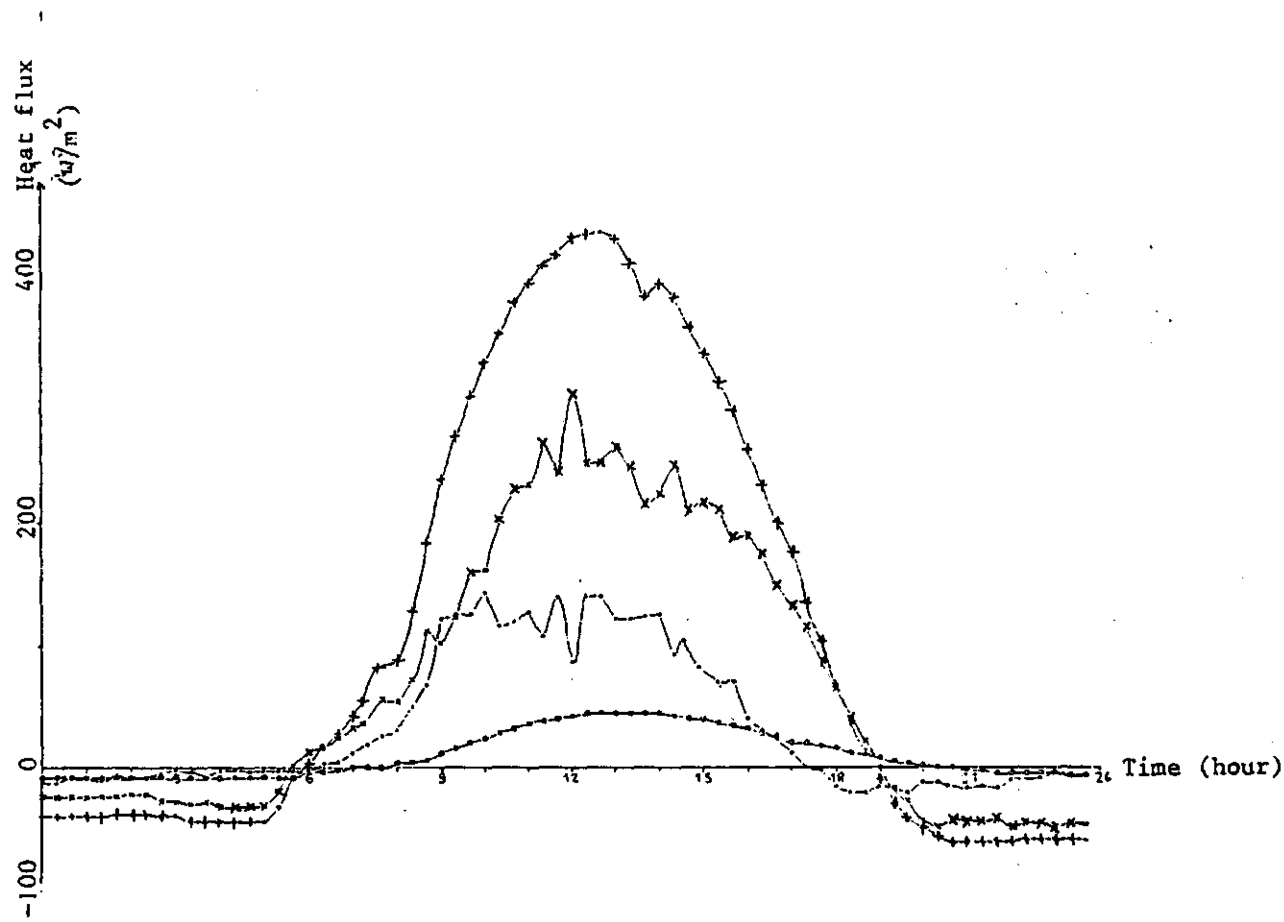


FIGURE 3.3.:Evolution of the heat fluxes during the day
----------- Data of the 10th of August 1983

+ :net radiation
▫ :soil heat flux
: :sensible heat flux
× :latent heat flux

3.2.3.The boundary layer:

It is because the largest changes in horizontal wind velocity , temperature and humidity usually take place in a vertical scale and very close to the surface that the air near the surface may be regarded as a boundary layer:the atmospheric boundary layer (ABL), according to Prandtl (1904).

The ABL is the lower part of the atmosphere where the nature and properties of the surface affect the turbulence directly.The horizontal gradients and vertical velocities are negligible as compared to the vertical gradients and horizontal velocities.

According to Brutsaert(1982),the ABL can be divided in several parts:

-The interfacial sublayer is the region nearest to the surface. The structure,height and density,of the roughness elements is important . The viscous effects are also non negligible.

-Above,is the inner region,where the flow is strongly affected by the surface.In this layer,also called surface sublayer,the vertical turbulent fluxes keep a value close to the one at the surface.For water vapour and in absence of condensation,the flux is constant.In the lower part of the surface sublayer,called the dynamic sublayer,water vapour and sensible heat flux may be considered as merely passive admixtures.The effects of density stratification resulting from humidity,temperature gradients and of the Coriolis force are negligible.Under neutral conditions,the whole surface sublayer behaves as a dynamic layer.

-Over the inner region,is the outer region or defect layer where the fluxes may be considered as independant of the surface's structure.The transition between the inner and outer regions is made by a region of overlap,called matched layer or inertial sublayer.

-The upper limit of the boundary layer is indicated by an inversion.It is higher under unstable conditions than under neutral conditions.

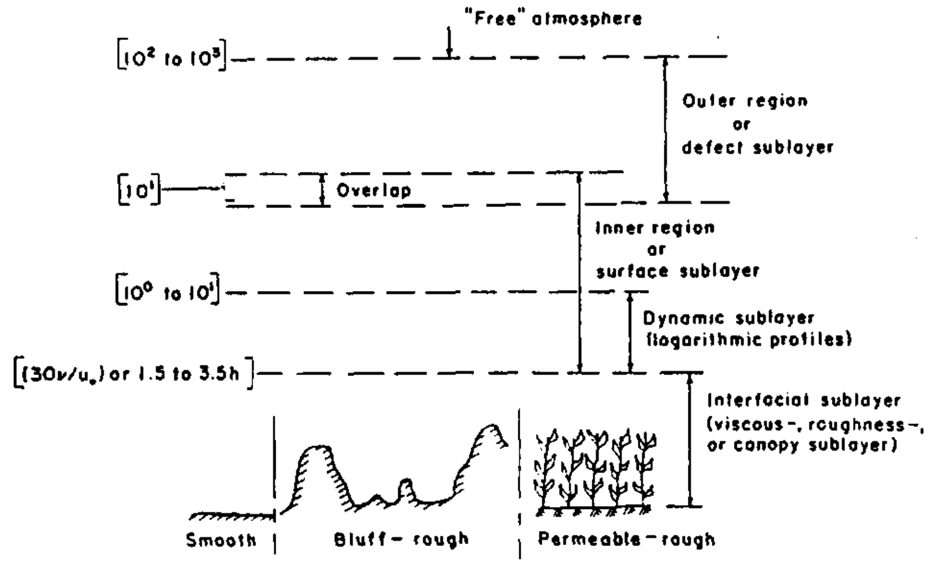


FIGURE 3.2.:Definition sketch showing orders of magnitude of the heights of the sublayers of the ABL;h is,in m,a typical height of roughness. (From Brutsaert 1982)

3.2.4.The mean profiles:

3.2.4.1.Under neutral conditions:

Numerous experiments (e.g.Tjachmann 1973,Reitsma 1978) have proved that in the dynamic sublayer,the profiles of the mean wind speed,mean temperature and mean specific humidity are all logarithmic functions of the altitude z.

a).The mean wind speed:u

The mean velocity gradient in a fluid of density ρ is determined by the shear stress at the wall τ_o and by the distance to the wall z.A dimensionless quantity of these variables is

$$\frac{u_*}{z \cdot (d\bar{u}/dz)} = k \qquad (3.4)$$

where $u_* = \sqrt{\tau_o/\rho}$ is the friction velocity

k is referred to as the von Karman's constant and literature gives values ranging from 0.35 to 0.47.

The logarithmic wind profile equation follows immediately by integration from (3.4)

$$u_2 - u_1 = \frac{u_*}{k} \ln (z_2/z_1) \qquad (3.5)$$

for 2 levels in the dynamic sublayer

$$u = \frac{u_*}{k} \ln (z/z_{om}) \qquad \text{for } z >> z_{om} \qquad (3.6)$$

zom is an integration constant.whose dimension is length,and for which value the mean wind speed becomes hypothetically zero.It is the roughness length for momentum.It may be obtained from the semi-logarithmic graph of mean velocity versus elevation:zom is the intercept on the y axis.For rough surfaces,the reference level of the wind speed is difficult to determine.In most cases ,it is situated between the tops and the bases of the roughness elements.This problem is solved by defining z=0 at the bases of the obstacles and introducing a shift in reference level for the z-coordinate.

$$S_o \text{ (3.4) becomes } \frac{u_*}{(z - d_o) \cdot (d\bar{u}/dz)} = k \qquad (3.7)$$

$$\text{and (3.6) becomes } u = \frac{u_*}{k} \ln \left(\frac{z-d_o}{z_{om}}\right) \qquad (3.8)$$

where do is called the zero-plane displacement height.
Literature(e.g.Brutsaert 1975) gives values of zom varying from 0.07.hcrop to 0.13.hcrop and of do between 0.65.hcrop and 0.5.hcrop.(hcrop means the height of the crop).zo=0.1.hcrop,do=0.5.hcrop (3.9) seem to be reasonable values.

b).The mean specific humidity:q

The dimensional approach used for the wind velocity profile can be extended to the mean specific humidity and other quantities as the temperature.The profile equations for the specific humidity and temperature are thus written in the same formulation than as for the mean wind speed(Similarity theory of Monin-Obukhov,1954).

A decrease in specific humidity with elevation can be explained by an upward water vapour flux.The rate of decrease of water vapour concentration with elevation ($d\bar{q}/dz$) in a fluid of density ρ is linked to the flux of water vapour at the surface($E = \rho.(w'q')$ where E is the evaporation rate at the surface,w' and q' are the turbulent components of the vertical wind speed and the specific humidity) and to the dynamics of the flow,expressed by τo,z-do and $d\bar{u}/dz$.
A dimensionless combination of these variables is

$$\frac{E}{u_* \cdot (z-d_o) \cdot \rho(d\bar{q}/dz)} = -k_v \qquad (3.10)$$

where $k_v = a_v \cdot k$ is the Von Karman constant for water vapour

av is the ratio of eddy diffusivity for water vapour and eddy viscosity for momentum under neutral conditions.Dyer (1974) suggested the value of 1.0 for av.

As for the mean wind speed,(3.10) can be integrated between two arbitrary levels z1 and z2 in the dynamic sublayer,yielding

$$q_1 - q_2 = \frac{E}{a_v \cdot k \cdot u_* \cdot \rho} \ln \left(\frac{z_2 - d_o}{z_1 - d_o}\right) \qquad (3.11)$$

or between the surface and a level in the dynamic sublayer

$$q_s - q = \frac{E}{a_v \cdot k \cdot u_* \cdot \rho} \ln \left(\frac{z - d_o}{z_{ov}}\right) \quad \text{for } z >> z_{ov} \qquad (3.12)$$

zov is the roughness length for water vapour.

c).The mean potential temperature:

The potential temperature is the temperature which would result if the air were brought adiabatically to a standard pressure level of 1000 mbar.

Analog to the specific humidity,one can write

$$\frac{H}{u_* \cdot (z-d_o)\ \rho\ Cp\ (d\bar{\Theta}/dz)} = -k_H \qquad (3.13)$$

where K_H is the Von Karman constant for sensible heat

H is the sensible heat flux.
ah is the analog of av for sensible heat, its value is assumed to be 1.0.

The integration of (3.13) leads to

$$\Theta_1 - \Theta_2 = \frac{H}{a_h \cdot k \cdot u_* \cdot \rho \cdot Cp} \ln \left(\frac{z_2 - d_o}{z_1 - d_o}\right) \qquad (3.14)$$

$$\Theta_s - \Theta = \frac{H}{a_h \cdot k \cdot u_* \cdot \rho \cdot Cp} \ln\left(\frac{z - d_o}{z_{oh}}\right) \qquad (3.15)$$

In a first approach, it can be assumed that (i) $z_{om}=z_{ov}=z_{oh}$ and (ii) the displacement height is the same for momentum, water vapour and heat transfer.

3.2.4.2. Profiles at non-neutral stability conditions:

Very often, the air is thermically stratified and the influence of stability has to be taken in account in the profiles relations. From a dimensional analysis, Obukhov(1946) introduced the stability length L, defined by

$$L = \frac{-\rho\, u_*^3}{k \cdot g \cdot \left(\frac{H}{T \cdot Cp} + 0.61\, E\right)} \qquad (3.16)$$

g is the gravity acceleration (9.81m/s2)
H and E are in kg/s/m2

The minus sign and the Von Karman's constant were originally introduced for convenience. Thus, L is positive for stable, negative for unstable and infinitely large for neutral conditions.
A dimensionless and convenient variable is

$$\xi = \frac{z - d_o}{L} \qquad (3.17) \quad \text{(Monin and Obukhov,1954)}$$

In the original formulation of Obukhov's length, the effect of the water vapour expressed in (3.16) by the term 0.61.E was not included. Even now, it is not often used and this point will be discussed in section 5.1.2.

This parameter can be related to another stability parameter introduced by Richardson (1920). Without including the effect of the water vapour, Richardson's number is written:

$$Ri = \frac{g}{T} \cdot \frac{d\bar{\Theta}/dz}{(d\bar{u}/dz)^2} \qquad (3.18)$$

According to the relations (3.4) and (3.13), Ri can be developped in the following way:

$$Ri = \frac{g}{T}\left[\frac{H}{u_*(z-d)\,\rho\, Cp\, k}\right]\left[\frac{(z-d_o)\,k}{u_*}\right]^2 \qquad (3.19)$$

$$\text{So} \quad Ri = \frac{kg\, H/T\, cp}{\rho\, u_*^3} = \frac{z-d_o}{L} = \xi \qquad (3.20)$$

The relation (3.10) describing the flux-profile relationship of water vapour becomes

$$\frac{-k \cdot u_* \cdot (z \cdot d_o) \cdot \rho}{E} (d\bar{q}/dz) = \phi_{sv}(\xi), \qquad (3.21)$$

where sv is supposed to be a universal function of .

In the same way, ϕ_{sm} and ϕ_{sh} are defined by

$$\frac{k(z-d_o)}{u_*} \frac{d\bar{u}}{dz} = \phi_{sm}(\xi) \qquad (3.22)$$

$$-\frac{k\ u_*\ (z-d_o)\ \rho\ Cp}{H} \left(\frac{d\bar{\Theta}}{dz}\right) = \phi_{sh}(\xi) \qquad (3.23)$$

Under neutral conditions ,these functions become :

$$\phi_{sv} = a_v^{-1},\ \phi_{sm} = 1,\ \phi_{sh} = a_h^{-1} \qquad (3.24)$$

Equations (3.21) to (3.23) lead to the following profile relations after integration:

$$\bar{q}_1 - \bar{q}_2 = \frac{E}{k \cdot u_* \cdot \rho} [\Phi_{sv}(\xi_2) - \Phi_{sv}(\xi_1)] \qquad (3.25)$$

$$\bar{u}_1 - \bar{u}_2 = -\frac{u_*}{k} [\Phi_{sm}(\xi_2) - \Phi_{sm}(\xi_1)] \qquad (3.26)$$

$$\bar{\Theta}_1 - \bar{\Theta}_2 = \frac{H}{k \cdot u_* \cdot \rho \cdot Cp} [\Phi_{sh}(\xi_2) - \Phi_{sh}(\xi_1)] \qquad (3.27)$$

To preserve the idea of the extension of the logarithmic profiles to the non-neutral conditions,the relations (3.25) to (3.27) can be written as:

$$\bar{q}_1 - \bar{q}_2 = \frac{E}{a_v \cdot k\ u_*\ \rho} \left[\ln\left(\frac{\xi_2}{\xi_1}\right) - \Psi_{sv}(\xi_2) + \Psi_{sv}(\xi_1)\right] \qquad (3.25')$$

$$\bar{u}_1 - \bar{u}_2 = -\frac{u_*}{k} \left[\ln\left(\frac{\xi_2}{\xi_1}\right) - \Psi_{sm}(\xi_2) + \Psi_{sm}(\xi_1)\right] \qquad (3.26')$$

$$\bar{\Theta}_1 - \bar{\Theta}_2 = \frac{H}{a_h\ k\ u_*\ \rho\ Cp} \left[\ln\left(\frac{\xi_2}{\xi_1}\right) - \Psi_{sh}(\xi_2) + \Psi_{sh}(\xi_1)\right] \qquad (3.27')$$

where,similar to the suggestion by Panofsky (1963),the Ψ -functions are defined by:

$$\Psi_{sv}(\xi) = \int_{zov/L}^{\xi} [1 - a_v\ \phi_{sv}(x)] \frac{dx}{x} \qquad (3.28)$$

$$\Psi_{sm}(\xi) = \int_{zom/L}^{\xi} [1 - \phi_{sm}(x)] \frac{dx}{x} \qquad (3.29)$$

$$\Psi_{sh}(\xi) = \int_{zoh/L}^{\xi} [1 - a_h \phi_{sh}(x)] \frac{dx}{x} \qquad (3.30)$$

where ψ sv,ψ sh, sm are universal functions.

A large amount of experiments and research has been done on the universal functions(e.g.Businger 1966, Paulson 1970, Dyer 1971, Monin and Yaglom 1971,Van Ulden and Holtslag 1985).At present,it is generally assumed that the same formulations can be taken for Ψ sv and Ψ sh but not for ψsm.The expressions used for this study are given in the next chapter.

3.2.5.The three methods based on profiles:

3.2.5.1.The indirect method:

The indirect method is based on the energy budget equation as written by De Vries(3.2)

$$Rn = H + E + G \qquad (3.31)$$

The calculation of H is possible from the data of dry-bulb temperature and wind speed profiles using equation (3.27).Then the evapotranspiration is indirectly determined by (3.31).

3.2.5.2.The Bowen ratio method:

The bowen ratio ,which is the ratio of the sensible heat flux and latent heat flux is a very useful concept.It is formulated by the equation

$$\beta = \frac{H}{E} \qquad (3.32)$$

It is of great importance because these two fluxes are generally treated together.The sensible heat can be considered as an admixture of air,just like the latent heat is an admixture of water vapour.Thus the mechanisms of transport of these scalar fluxes are similar,which allows to manipulate them similarly.

The Bowen ratio can be calculated from the dry-bulb and wet-bulb temperature profiles.

Assuming that the transfer coefficients of heat and water vapour are equal,it can be shown that

$$\beta = \gamma \frac{\partial T}{\partial e} \qquad (3.33) \qquad \text{(Monteith 1973)}$$

where γ is the psychrometric constant: $\gamma = \frac{Cp \cdot p}{\epsilon \cdot Le}$ (3.34)

and e is the water vapour pressure at the temperature T
At 288 K and under a pressure of 1000 mbar, the numerical values are the following:

.Cp=1.01 10 J/^{0}K/kg
.p=1000 mbar
.ε is the ratio of the mole weigths of water vapour and of dry air =0.622
.Le=2.465 10^6 J/kg

γ can be calculated: =0.66mbar/^{0}K

A parcel of air can be characterized by its vapour pressure e and its temperature Td. If it is cooled, it becomes saturated at a certain temperature Tw and a certain pressure es(Tw), for which Monteith(1973) showed the

$$e = e_s\,(Tw) - \gamma\,(Td - Tw) \qquad (3.35)$$

Considering two systems (e1,Td1,es(Tw1),Tw1) and (e2,Td2,es(Tw2),Tw2) we obtain the difference e by the relation

$$\Delta e = e_s(Tw2) - e_s(Tw1) - \gamma\Delta Td + \gamma\Delta Tw \qquad (3.36)$$

If s is the slope of the non-linear saturation water vapour pressure curve versus temperature, then es(Tw2)-es(Tw1)=s.(Tw2-Tw1) as a first order approach and it follows:

$$\Delta e = s \cdot \Delta Tw - \gamma\Delta Td + \gamma\Delta Tw = (s + \gamma)\,\Delta Tw - \gamma\Delta Td \qquad (3.37)$$

Then

$$\beta = \frac{\gamma\Delta Td}{(s+\gamma)\,\Delta Tw - \gamma\Delta Td} \qquad (3.38)$$

which can also be written:

$$\beta = \frac{1}{\left(\frac{s+\gamma}{\gamma}\right)\left(\frac{\Delta Tw}{\Delta Td}\right) - 1} \quad \text{for } \Delta Td \neq 0 \qquad (3.39)$$

$$\beta = 0 \text{ for } \Delta Td = 0$$

In this method, both the Bowen ratio and the energy budget are employed. Combining (3.31) and (3.32), the latent heat flux can be obtained by eliminating the sensible heat flux or the sensible heat flux by eliminating the latent heat flux.

thus

$$E = \frac{Rn - G}{1 + \beta} \qquad (3.40)$$

and

$$H = \frac{\beta}{1 + \beta}(Rn - G) \qquad (3.41)$$

3.2.5.3. The direct method:

The evapotranspiration can be directly calculated using all the profiles of wet and dry bulb temperatures and wind velocities. The basic equation is (3.25)

The stability functions for heat and for vapour are the same, av is assumed to be 1, so that E can be calculated from the following equation, rearranging equation (3.25)

$$E = \Delta q \cdot k \cdot \rho \cdot \frac{u_*}{\ln\left(\frac{\xi_2}{\xi_1}\right) - \Psi_h(\xi_2) + \Psi_h(\xi_1)} \quad (3.42)$$

q has to be expressed in functions of the wet and dry-bulb temperatures differences. It is valid that

$$q = \frac{\varepsilon}{p} e \quad (3.43)$$

From the definition of γ (3.34) we get

$$\Delta q = \Delta e \frac{Cp}{Le \cdot \gamma} \quad (3.44)$$

Then, replacing Δe by the expression (3.37), the definite formulation for the calculation of E becomes

$$E = \frac{(s+\gamma) \cdot \Delta Tw - \gamma \Delta Td}{\gamma \cdot Le} \cdot k \cdot \rho \cdot Cp \cdot \frac{u_*}{\ln\left(\frac{\xi_2}{\xi_1}\right) - \Psi_h(\xi_2) + \Psi_h(\xi_1)} \quad (3.45)$$

Introducing Le, E is expressed in kg/s/m2. Without this term, it is in W/m2.

The direct method can also be expressed in terms of Bowen ratio, since

$$\frac{k\, u_*\, \rho\, Cp\, \Delta Td}{\left[\ln\left(\frac{\xi_2}{\xi_1}\right) - \Psi_{sh}(\xi_2) + \Psi_{sh}(\xi_1)\right]}$$ represents H and $$\frac{\gamma \Delta Td}{(s+\gamma)\ \Delta Tw - \gamma \Delta Td}$$

is β. So that $E = H/\beta$, which is the definition of the Bowen ratio.

3.3. The approaches used for calculation of potential evapotranspiration

The notion of potential evapotranspiration had been introduced first by Thornthwaite in 1948, in the context of the classification of climate. It is referred to as the maximum rate of evapotranspiration from a large area completely covered by an actively growing vegetation which is sufficiently supplied by water.

3.3.1. Penman's formula:

The first formula was developped by Penman (1948), for an open water surface. It can be applied for any wet surface, in principle, accounting for the appropriate wind function. When the surface is wet, the surface specific humidity may be assumed to be the saturation value at the surface temperature: $q_s = q^*(T_s)$.

Penman combined the aerodynamic formulas for the vertical transfer of water vapour and sensible heat (Dalton's law:$E=f(u).(es^{*}-ea)$ as defined in the first part of this chapter,equation (3.1)) with the energy balance balance equation and he derived the formula

$$E = \frac{1}{Le} \cdot \frac{s(Rn-G) + f(u) \cdot \Delta e}{s + \gamma} \qquad (3.47)$$

with E expressed in kg/m2/s and Le in J/kg.

γ:psychrometric constant

s:slope of the curve relating the saturation vapour pressure versus temperature.

$Ea=f(u).\Delta e$ is the drying power of the air and its expression varies with the formulation of the wind function f(u).

Penman (1948) originally proposed

$$f(u)=0.26.(1+0.54.u2) \qquad (3.48)$$

u2 is the mean wind speed in m/s at 2m above the surface.The constants require that Ea is in mm/day and the vapour pressure in mbar.Penman proposed later a 'weaker' wind function,as a correction to (3.48):

$$f(u)=0.26.(0.5+0.54.u2) \qquad (3.49)$$

The use of empirical wind functions is adequate for calculations on a period of one day or longer.

Penman's formula has been the basis of a lot of continued studies. The most important,used in this study,are these of Priestley and Taylor (1972),Thom and Oliver(1977) and Makkink(1957).

3.3.2.The formula of Priestley and Taylor:

The idea is that over land,the sum of the latent and sensible heat fluxes is strongly affected by the net radiation.The partition of energy between the evapotranspiration (E) and the sensible heat flux (H) depends on the dryness of the ground and of the surface temperature.

Priestley and Taylor stated that for an infinitely large saturated surface,the fluxes will approach the ratio

$$\frac{E}{H} = \frac{s}{\gamma} \qquad (3.50)$$

This is only under certain conditions on the temperature and the humidity: the range of variation of the temperature is not too large in order to linearize the qs,T curve.

So E is proportional to s and H to γ.Then,neglecting the heat storage below the surface and introducing $Rn=E+H$,it follows

$$E = Rn \cdot \frac{s}{s + \gamma} \qquad (3.51)$$

In a more general way, it can be assumed that

$$\frac{E}{Rn} = \alpha \cdot \frac{s}{s + \gamma} \qquad (3.52)$$

is related to the Bowen ratio by the relation (3.53):

$$\beta = \frac{1 - \alpha \frac{s}{s + \gamma}}{\alpha \frac{s}{s + \gamma}} \qquad (3.53)$$

Priestley and Taylor applied data from different experiments made before, to calculate α.(CSIRO, Commonwealth Scientific and Industrial Research Organization, over land (1963), and over the oceans (1968); University of Wisconsin, Black, over land (1968); Wangara expedition, over land (1967); University of Washington, Paulson, over the Indian ocean (1967)).
For large saturated and 'advection-free' surfaces, Priestley and Taylor (1972) concluded that the best estimate was β=1.26. Davies and Allen (1973) confirmed the value of 1.26 for well watered grass. But it seems (Mukammal et al (1977), Jury and Tanner (1975)) that may be larger and 1.28 is supposed to be a better value.

The relation $E = 1.28 \frac{s}{s + \gamma} Rn$ (3.54)

shows that the conditions of minimal advection ($E = (s/s+\gamma).Rn$) do not occur in fact. It shows that the term $(\gamma/s+\gamma).Ea$ in the Penman formula which represents the large-scale advection effects accounts for roughly one-fourth of the evaporation.

This empirical formulation, with α= 1.28, fails to be valid under circumstances, for which the evaporation is determined much stronger by large-scale advection. Under dutch circumstances for instance, the formulation fails from october to March/April.

3.3.3. The formula by Thom and Oliver

The starting point is a formulation proposed by Monteith in 1973

$$E = \frac{s \cdot Rn + \rho \cdot Cp \cdot \Delta e/r_a}{s + \gamma \left(1 + \frac{r_s}{r_a}\right)} \qquad (3.55)$$

where ra and rs are diffusive resistances in s/m.
ra expresses the aerodynamic resistance to the diffusion of water vapour from the surface itself, where vapour pressure has an unknown value e_o, to some reference level; above, where the vapour pressure is e:

$$r_a = \frac{\rho Cp}{\gamma} \left(\frac{e_0 - e}{E}\right) \qquad (3.56)$$

rs is the analogous for a saturated region (es_0) to the surface:

$$r_s = \frac{\rho Cp}{\gamma}\left(\frac{e_{s0} - e_0}{E}\right) \qquad (3.57)$$

For a vegetated surface,rs is considered to be the canopy resistance.

Thom and Oliver (1977) formulated ra for any surface under neutral conditions as

$$ran = [\ln(z/zo)]^2 / k^2 .u \qquad (3.58)$$

and under neutral conditions as

$$r_a = [\ln(z/z_0) - \Psi]\ [Ln(z/z_0 - \Psi']/K^2 u \qquad (3.59)$$

where ψ and ψ' are stability functions as formulated before.

ra can be related to Penman's Ea (written as Eap)in the following way;

$$\gamma\ Eap = \frac{\rho Cp}{r_{ap}} \Delta e \qquad \text{or} \qquad r_{ap}\ \frac{\rho\ Cp\ \Delta e}{\gamma Eap}$$

$$\text{with } Eap = 0.26 \cdot \Delta e\ f(u) \cdot 28.5 \text{ (in } w/m^2\text{)} \qquad (3.60)$$

$$\text{and } \rho \approx 1.21\ kg/m^3$$

$$Cp \approx 1.01\ 10^3\ J/kg/^oK$$

$$\gamma = 0.66\ mbar/K$$

It yields : rap=250/f(u) (s/m).

This is in fact the resistance encountered by water vapour in diffusing from the open water surface up to a height of 2m,as considered by Penman.

Under neutral conditions,Penman's resistance is theoretically defined as

$$ranp = [\ln(z/zop)]^2 / k^2 .u$$

where zop is the open water surface aerodynamic roughness.Thom and Oliver proposed zop=1.37 mm.

The relation between ran and ranp is assumed also to be valid for ra and rap.

$$\frac{ran}{ranp} = \frac{[\ln(z/zo)]^2}{[\ln(z/zop)]^2} = m^{-1} = \frac{ra}{rap} \qquad (3.61)$$

With rap=250/f(u),ra can be written as

$$ra = m^{-1} .rap = \frac{[\ln(z/zo)]^2}{[\ln(z/zop)]^2} . \frac{250}{f(u)} \qquad (3.62)$$

Because $250/[\ln(z/zop)]^2$ is 4.72,

$$ra = 4.72\ [\ln(z/zo)]^2/(1+0.54.u) \qquad (3.63)$$

And m is defined by: $m = [\ln(z/zop)/\ln(z/zo)]^2$ (3.64)

Thom and Oliver defined then E, after rearranging the Monteith equation, to

$$E = \frac{sRn + \gamma_m\ Eap}{s + \gamma(1+n)} \qquad (3.65)$$

with $n = rs/ra$. They proposed for grass under well watered circumstances the value of 65 s/m for rs.

The formula can be completed by including the soil heat flux, so that the definite equation is

$$E = \frac{s(Rn-G) + m \cdot \gamma \cdot \Delta e \cdot f(u)}{s + \gamma\ (1 + n)} \qquad (3.66)$$

The Thom and Oliver formula can be applied potentially to surfaces of restricted availability of water. In that case, the value of rs will increase and no longer potential evapotranspiration happens.

3.3.4. The formulation of Makkink:

Makkink's formula is completely empirical. He stated

$$E = 0.65\ \frac{s}{s+\gamma}\ Rg \qquad (3.67)$$

where Rg is the incoming short-wave radiation (or global radiation).
If the soil heat flux is taken in account, with the condition of same weight as in the Priestley-Taylor formulation, the formulation (3.68) is obtained:

$$E = 0.65\ \frac{s}{s+\gamma}\ (Rg - 2G) \qquad (3.68)$$

It may be remarked that if the net radiation is half of the global radiation, the formulations of Makkink and of Priestley and Taylor will yield the same results.

Makkink's formula is less sensitive to a limited period of use since Rg will be positive also during winter period. This formula may be applied during the whole year.

3.4. The advection-aridity method:

In order to calculate the actual evapotranspiration from meteorological data, commonly used in the various equations of the potential evapotranspiration, Brutsaert and Stricker (1979) proposed an heuristic approach called the advection-aridity method.

The method is based on two concepts: (i) the relationship between large-scale advection and potential evapotranspiration; (ii) a complementary relationship between potential and actual evapotranspiration.

Concerning the first concept, Penman's formula of potential evapotranspiration $E = \frac{s}{s+\gamma}(Rn - G) + \frac{\gamma}{s+\gamma} Ea$ may be decomposed in two terms:

$\frac{s}{s+\gamma}(Rn - G)$ may be considered as the lower limit of evaporation from moist surface. This was the base of Priestley and Taylor's work.

$\frac{\gamma}{s+\gamma} Ea$ is interpreted as a measure of the departure from equilibrium in the atmosphere. In the absence of clouds or radiative divergence, this departure would stem from large-scale advection effects.

The second concept was introduced by Bouchet (1963). He considered a large and uniform surface, in which the actual evapotranspiration is E and Ep is the potential evapotranspiration which would take place if only the available energy were the limiting factor.

Under conditions when E equals Ep, it is denoted by Epo.

If E decreases below Epo (for other reasons than a non-availability of energy), an amount of energy ql becomes available.

$$ql = Epo - E \qquad (3.69)$$

If the energy balance remains unaffected, this energy flux increases Ep and

$$Ep = Epo + ql \qquad (3.70)$$

The complementary relationship between the actual and potential evapotranspiration is derived from (3.69) and (3.70):

$$Ep + E = 2.Epo \qquad (3.71)$$

The potential evapotranspiration as defined by Priestley and Taylor (3.54) represents Ep under conditions of minimal advection and thus it corresponds to Epo according to Bouchet.

The formulations of Penman and of Thom and Oliver can be applied as representations of Ep. They are sensitive to large-scale advection in their second part of the formula.

Brutsaert and Stricker (1981) proposed two formulations:

$$E = 2.Ep(\text{Priestley-Taylor}) - Ep(\text{Penman})$$

or

$$E = 2.Ep(\text{Priestley-Taylor}) - Ep(\text{Thom-Oliver})$$

and applied these formulations to the data of the Hupselse Beek area for the very dry year 1976.

CHAPTER 4:THE CALCULATIONS

4.1.Actual evapotranspiration:

The three methods based on temperature and wind profiles measurements described in the previous chapter are used for the calculations of the actual evapotranspiration with a timestep of 20 minutes.Using such a short timestep is required by the method:the conditions of stability of the atmosphere for the heat tranfer are often changing.Reliable results are then obtained with the shortest timestep.From the 20-minutes results, average values are calculated over one hour ,one day and the daylight period(considered from 8h00 to 18h00).

The measurements were done between the 1st of May and the 31st of October every year.Nevertheless, some periods are excluded,when some measurements of one,of several or of all the components were not done.In the file of results,the missing data are written 9.99 for the friction velocity and 999 for the sensible and latent heat fluxes.

4.1.1.Indirect method:

4.1.1.1.calculation of the sensible heat flux:

a).Formulations and process:

The equations (3.25) and (3.26) are the base of the calculations of the sensible heat flux:

$$u_* = \frac{k\,[u(z'_2) - u(z'_1)]}{\ln\left(\frac{z'_2 - d_o}{z'_1 - d_o}\right) - \Psi_M(\xi'_2) + \Psi_M(\xi'_1)} \qquad (4.1)$$

$$H = \frac{-\rho.u^*.\,Cp\,k\,[\Theta(z_2) - \Theta(z_1)]}{\ln\left(\frac{z_2 - d_o}{z_1 - d_o}\right) - \Psi_H(\xi_2) + \Psi_H(\xi_1)} \qquad (4.2)$$

```
     Measurement of    |   Measurement of
     the temperature   |   the wind velocity
                       |
                       |
                       |- z'=9.48m
                       |
          z =7.14m    -|
                       |
                       |
                       |- z' =3.97m
          z =3.15m    -|
                       |- z' =2.14m
          z =1.30m    -|
                       |
```

FIGURE 4.1 :The heights of measurements of the temperature and wind velocities

The height of the grass is estimated at 0.1m and the values of do and zo are zo=0.01m and do=0.05m(from (3.9)).
Different heights can be chosen for the measurements of the temperature and the wind velocity because we can consider that up to a height of 50m, the vertical fluxes are constant(constant fluxes layer).The chosen heights are reported in figure 4.1.

The flux calculation is done by a iterative numerical process.

From the data of wind velocity difference,u* is calculated with (4.1) with the stability functions set to 0 (neutral conditions).Then,with u* and the value of the temperature difference,H is calculated,the stability functions being 0.

From these first values of the friction velocity and the sensible heat flux,a value of the Monin-Obukhov's stability length can be calculated.The complete formulation (3.16) is not employed,the equation which is used here is

$$L = \frac{-\rho \ u_*^3}{kg \cdot H/T \cdot Cp} \qquad (4.3)$$

This value is then compared to an initial value of L for near-neutral conditions(-100.000 under unstable conditions or 100.000 under stable conditions).The calculations stop when the difference by convergence between the initial value and the calculated value is assumed being small enough to give a final result.Otherwise,new iterative loops are done.The stability functions are :

-For stable conditions:

$$\Psi_M = \Psi_H = - \left[a\xi + b\left(\xi - \frac{c}{d}\right) \exp\left(-d\xi\right) + \frac{b.c.}{d}\right] \qquad (4.4) \qquad \text{(Holtslag 1987)}$$

where $\xi = \frac{z - d_0}{L}$

a=0.7 ; b=0.75 ; c=5 ; d=0.35

-For unstable conditions:

$$\Psi_M = 2\ln\left(\frac{1+X}{2}\right) + \ln\left(\frac{1+X^2}{2}\right) - 2 \text{ Arctg } (X) + \frac{\pi}{2} \qquad (4.5)$$

$$\Psi_H = 2\ln\left(\frac{1+X^2}{2}\right) \qquad (4.6)$$

where $X = (1 - 16\ \xi)^{1/4}$ (4.7)

(Paulson 1970)

The iteration stops when the value of L is constant(difference between two consecutive values less than 0.1) or after 20 loops.

b).Development of the program:

SEQUENCE FOR ONE LEVEL:

1)Check of the temperature profile:
-if it is a dummy value:no result(999)
-else:The adiabatic correction is made on the temperature difference:

$$\Theta(z_1) - \Theta(z_2) \text{ becomes } \Theta(z_1) - \Theta(z_2) - \Gamma d(z_1 - z_2) \qquad (4.8)$$

Γd is known as the dry adiabatic lapse rate,which is the vertical rate of temperature decrease by work,the displaced air parcel would undergo if the parcel would be completely dry.

2)Check of the option of calculation of u*:it is depending on the value of the wind velocity at 3.97m above the soil surface:
if it is too small(lower than 1.50m/s),the calculation of u* is made between 3.97m and the surface,more precisely zom+do.The measured wind profile is in this case too small to be trusted so that it is better calculating the difference between this height and the ground levelmore where the wind velocity is theoretically 0.

3)State of the atmosphere for heat:the new value of $\Delta\Theta$ is giving the information about the stability of the atmosphere:

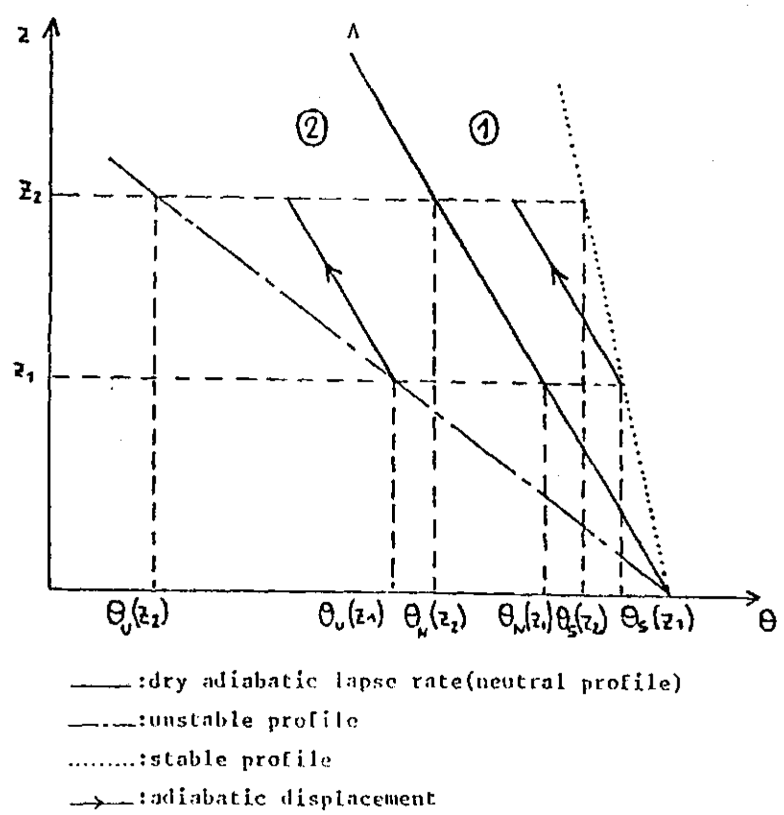


FIGURE 4.2:State of the atmosphere for the heat transfer:diagram(Θ,z)

The curve $\Theta = \Gamma d.z$ is dividing the domain (Θ,z) in two zones.
Given three temperature gradients, for the same heights z1 and z2(z1<z2):

$\Theta_N(z_2) - \Theta_N(z_1) = \Gamma d \cdot (z_2-z_1)$ line A

$\Theta_u(z_2) - \Theta_u(z_1) > \Gamma d \cdot (z_2-z_1)$ zone 1

$\Theta_s(z_2) - \Theta_u(z_1) < \Gamma d \cdot (z_2-z_1)$ zone 2

If a parcel of air which is at the altitude z1 and temperature $\Theta u(z1)$ is raised adiabatically, it will have a temperature at z2 higher than $\Theta u(z2)$ (temperature of the surrounding air). So it will be lighter and goes on raising: the conditions are unstable.
On the opposite, a parcel of air at the altitude z1 and with a temperature $\Theta s(z1)$ will, after an adiabatic raising, have a temperature lower than $\Theta s(z2)$, so it will go down because it is heavier than the surrounding: the conditions are stable.

4) Iterative calculation: all the options, stability functions are now known and the calculations by the iteration numerical process as described before can then be done.

This sequence is repeated three times for the levels:
- -Lower gradient:1.30m-3.15m:results :H1
- -Upper gradient:3.15m-7.14m:results :H2
- -Global gradient:1.30m-7.14m:results :H3

When the second serie of temperature measurements from the psychrometer is dry-bulb temperature, we get :
- -For the lower gradient:H5
- -For the upper gradient:H6
- -For the global gradient:H7

4.1.1.2. calculation of the latent heat flux from the sensible heat flux and the energy balance

In the report, this method is called either indirect method, either energy balance method. The evapotranspiration calculated by this method is written EHx, with x numerically defined as before.

The basic equation is the energy budget equation(3.2)

$$Rn = G + H + EH \qquad (4.9)$$

The net radiation (Rn) and the soil heat flux (G) are measured. H is calculated by the profile method. All the components are in W/m^2. EH is derived from:

$$EH = Rn - G - H \qquad (4.10)$$

When the wet-bulb measurements are available , the two other methods related to the profiles can be used.

4.1.2. The Bowen ratio method:

4.1.2.1. The formulations:

a). The Bowen ratio:

The Bowen ratio is the ratio of the sensible heat to the latent heat flux:

$$\beta = \frac{H}{E} \qquad (4.11)$$

β is calculated from measurements of temperature and water vapour pressure as explained in section 3.2.5.2., formula (3.39).

Calculation of s:

s is calculated by Clapeyron's formula:

s=(as + 2.at.Tw + 3.au.Tw + 4.av.Tw) * 1.333

where:

Tw is the wet-bulb temperature measurement at 3.15 m above the surface, in ^{0}K

as, at, au, av are numerical coefficients which values are the following:

as=0.333
at=0.01065
au=0.0001873
av=0.00000322

b). Calculation of the latent heat flux from the energy budget equation and the Bowen ratio

The evapotranspiration can be calculated from the energy budget equation(4.9) and the definition of the Bowen ratio (4.11) by the relation

$$E = \frac{Rn - G}{1 + \beta} \qquad (4.12)$$

Equation (4.12) produces a singularity when β =-1 but Tanner (1960) explained that this is not an important problem over an active vegetation, since this situation occurs only when H is low, around sunset and sunrise or occasionnally at night.
Equation (4.12) is not used if β is lower than -0.5 to avoid the problem of a very small denominator.

4.1.2.2: Development of the program:

1) Check of the temperature measurements: no calculation if it is a dummy value (result: 999)

2) If ΔTw and ΔTd are both nil, equation (3.38) gives an infinitely large value of β and then E is nil.

3)If ΔTd is nil, then the conditions are neutral. There is no sensible heat flux and the energy budget equation yields the result for the evapotranspiration : $E = Rn - G$.

4)Outside these particular cases, the variable Hß is calculated by:

$$H\beta = \left(\frac{s+\gamma}{\gamma}\right) \left(\frac{\Delta Tw}{\Delta Td}\right) \qquad (4.13)$$

A Bowen ratio smaller than -0.5 corresponds to a value of Hß larger than -1 and smaller than 1. In this case, no calculation is done. Otherwise, the Bowen ratio is calculated from the formulas (3.39) and the evapotranspiration is calculated from equation (4.12)

The results are named EB1, EB2 and EB3 for the lower, upper and global levels.

4.1.3. The direct method:

4.1.3.1. The formulations:

The basic equation of this method is the equation of the humidity profile, where the difference between the specific humidity at two levels is expressed as a function of the wet and dry-bulb temperature differences, it is equation (3.45).

$$E = \frac{(s+\gamma) \cdot \Delta Tw - \gamma \Delta Td}{\gamma \cdot Le} \cdot k \cdot \rho \cdot Cp \cdot \frac{u_*}{\ln\left(\frac{\xi_2}{\xi_1}\right) - \Psi_h(\xi_2) + \Psi_h(\xi_1)} \qquad (4.14)$$

It has been noted in section 3.3.2 that this expression can be written with H and β : $E = H/\beta$. This is employed for the calculations and two different formulations are used whether Td is zero or not.

First, in both cases, the term $A = [(s+\gamma) . \Delta Tw - \gamma . \Delta Td]/\gamma$ is calculated.

Then,

- if $\Delta Td \neq 0$: $E = H * A / \Delta Td$ (4.15)

- if $\Delta Td = 0$: $E = \dfrac{u_* \cdot \rho \cdot Cp \cdot k \cdot A}{Ln\left(\frac{\xi_2}{\xi_1}\right)}$ (4.16)

4.1.3.2. Development of the program:

1)Check of the values of the temperature profiles.

2)Two options of calculation, according to the value of Td:
- if $\Delta Td \neq 0$: equation (4.15) is applied.
- if $\Delta Td = 0$: equation (4.16) is applied.

The results are named E1, E2, E3 for the three considered levels

For practical reasons, the calculations of the three methods, discussed, were executed in three programs, written in Fortran:

- SENSIB: calculations of the sensible heat fluxes with the first srie of temperature measurements (always dry-bulb), giving the values of H1, H2, H3.

- EVAPO: calculations with the second serie of temperature measurements producing:
  - H5, H6, H7 if they are dry-bulb temperatures (same procedure as in SENSIB).

  or

  - E1, E2, E3, EB1, EB2, EB3 if they are wet-bulb temperatures.

- EVAPOT: calculations of EH1, EH2, EH3 and EH5, EH6, EH7 if available and recording all the results.

The listings of the programs EVAPO and EVAPOT are in appendix. The listing of the program SENSIB is not given since it contains the same calculations as EVAPO.

4.1.4. The errors expected:

The theoretical error analysis is made according to Taylor's formulations. For instance, if $Y = f(X1,X2,X3)$, then $Y+\Delta Y = f(X1+\Delta X1, X2+\Delta X2, X3+\Delta X3)$. And from Taylor's analysis, it follows

$$\Delta Y = \frac{\partial f(x1)}{\partial x1}\Delta x1 + \frac{\partial f(x2)}{\partial x2}\Delta x2 + \frac{\partial f(x3)}{\partial x3}\Delta x3$$

and

$$\frac{\Delta y}{y} = \sum_{i=1}^{3} \frac{\partial f(Xi)}{\partial Xi}\frac{\Delta Xi}{y} = \sum_{i=1}^{3} \frac{\partial f(Xi)}{\partial Xi}\frac{\Delta Xi}{Xi}\frac{Xi}{Y}$$

$\Delta Xi/Xi$ represents the percentage of error on X.

4.1.4.1. Estimation of the error in the three methods for calculation of the actual evapotranspiration:

The three basic equations are:

- indirect method: $EH = Rn - G - H$ (4.17)
- direct method: $E = H / \beta$ (4.18)
- Bowen ratio method: $EB = (Rn - G) / (1 + \beta)$ (4.19)

where H is defined by equation (4.2) or

$$H = \frac{-\rho \cdot Cp \cdot k \cdot u_{*} \cdot \Delta Td}{Ln\left(\frac{\xi_2}{\xi_1}\right) - \Psi_H(\xi_2) + \Psi_h(\xi_1)} \quad (4.20)$$

For all the calculations of errors, it is assumed that the worst case is when all the terms contribute an equally signed error in E.

Estimating of the relative error on β with

$$\beta = \Delta Td \left[\left(1 + \frac{s}{\gamma}\right) \Delta Tw - \Delta Td\right]^{-1} \qquad (4.21)$$

Fuchs and Tanner (1970)showed that

$$\frac{\delta\beta}{\beta} = (1+\beta)\left[- \frac{\delta\Delta Td}{\Delta Td} + \frac{\delta\Delta Tw}{\Delta Tw} + \frac{\delta s}{s + \gamma}\right] \qquad (4.22)$$

Estimates of the errors on the evapotranspiration:

-Bowen ratio method:

$\delta EB/EB$ is directly found from equations (4.19) and (4.22)

$$\frac{\delta EB}{EB} = \frac{\delta(Rn-G)}{Rn - G} + \frac{\delta(1+\beta)}{1 + \beta} = \frac{\delta(Rn-G)}{Rn - G} + \beta \left[\frac{\delta\Delta Td}{\Delta Td} + \frac{\delta\Delta Tw}{\Delta Tw} + \frac{\delta s}{s + \gamma}\right] \qquad (4.23)$$

(Fuchs and Tanner,1970)

-Indirect and direct methods:

The theoretical error analysis had been made by Grant (1975) and he found the following equations:

$$\frac{\delta EH}{EH} = (1+\beta) \frac{\delta(Rn-G)}{Rn - G} + \beta \left[- \frac{\delta\Delta Td}{\Delta Td} + \frac{\delta\Delta u}{\Delta u} + \frac{2\delta do}{z-do}\right] \qquad (4.24)$$

$$\frac{\delta E}{E} = (1+\beta) \left[\frac{\delta\Delta Tw}{\Delta Tw} + \frac{\delta s}{s+\gamma} - \frac{\beta}{1 + \beta} \frac{\delta\Delta Td}{\Delta Td}\right] + \frac{\delta\Delta u}{\Delta u} + \frac{2\delta d}{z-d} \qquad (4.25)$$

It can be remarked that ΔTd is acting in the same way for the three methods since $\Delta Td/Td$ has the same weight in the three formulas (4.23),(4.24) and (4.25).

4.1.4.2.Comparison of the accuracy of the three methods:

-Direct method/Bowen ratio method:

The direct method will be more accurate than the Bowen ratio method if $\delta E/E < \delta EB/EB$,that means

$$\frac{\delta\Delta Tw}{\Delta Tw} + \frac{\delta s}{s+\gamma} + \frac{\delta\Delta u}{\Delta u} + \frac{2\delta do}{z-do} < \frac{\delta(Rn-G)}{RN - G} \qquad (4.26)$$

These different components have to be estimated according to the accuracy of the instruments used.
During daylight,typical values of ΔTw are in the range from 0.2 to 0.4^0C. The accuracy of the measurement can be estimated at 0.02^0C.The value of $\delta\Delta Tw/\Delta Tw$ is thus from 0.1 to 0.05.
s is varying of about 0.07 for one degree.The precision on the measurement of the temperature is of one tenth of a degree,so that $\delta s = 0.007$ seems a

reasonable value, $s+\gamma$ is about 1.5 and then $\delta s/s+\gamma$ is estimated to 0.005. From the calibration of the devices, $\delta(Rn-G)/Rn-G$ can be estimated at about 0.05.
$\delta\Delta u/\Delta u$ has a high value, about 0.1. This is due to the use of the cup anemometers which lead to a systematic overspeed because the deceleration is always slower than the acceleration due to the inertia of the device.
It is said in the litterature that do has to be taken within the range 0.5.h and 0.65.h. Choosing 0.5.h, the error is at maximum of 0.15.h. Then $\delta do/z-do$ is 0.15.h/z-0.5.h, which is for z=3m and do=0.1m, about 0.005.
These last two terms are thus negligible.

Using above mentioned estimates, it can be concluded that the inequality (4.26) is unlikely to be satisfied and that the Bowen ratio is giving more accurate results than the direct method.

-Indirect method/Bowen ratio:

The indirect method will give more reliable results than the Bowen ratio method if $\delta EH/EH < \delta EB/EB$, that means if the relation

$$\frac{\delta(Rn-G)}{Rn-G} - \frac{\delta\Delta u}{\Delta u} + \frac{2\delta do}{z-do} < \frac{\delta\Delta Tw}{\Delta Tw} + \frac{\delta s}{s+\gamma} \qquad (4.27)$$

is satisfied.
Considering the numerical values of the different terms, the left hand side of the inequality will be at about 0.05. It is thus difficult to draw a conclusion as for the comparison of the accuracy of the Bowen ratio method and indirect method.

4.1.5. The results:

Tables 4.1. and 4.2. show 20-min data for two different periods

In table 4.1., some results of the 19th of June 1983 are presented. No wet-bulb temperature measurements were done for this period. EB and E are not calculated and this appears as 888 in the files of results. On the other hand, two series of dry-bulb temperature were measured and U*5, U*6, U*7, H5, H6, H7, EH5, EH6, EH7 are the results of the friction velocity, sensible heat and latent heat fluxes calculated from these data. These values are comparable to these of U*1, U*2, U*3, H1, H2, H3, EH1, EH2, EH3 since they represent the same quantity, calculated from another measurement.

DL1 is value of the stability length for the lower level. It is positive at night, very high in absolute value around sunrise when the atmosphere is near-neutral(first positive and then negative) and negative during daylight.

WD is the wind direction in degrees with respect to the North and contains information with respect to the wind velocity and the friction velocity. The strength of the wind may be reduced for certain directions of wind, according to some obstruction or crops which are surrounding the meteorological station, at distances of at least 100-150m.

TABLE 4.1.:Results of the 19th of june 1983,from 9h00 to 14h20

DATE	RAIN	Rn	G	WD	U*1	U*2	U*3	U*5	U*6	U*7
DL1	E1	E2	E3		H1	H2	H3	H5	H6	H7
BETA1	EB1	EB2	EB3		EV1	EV2	EV3	EV5	EV6	EV7
831700900	0.00	334	19	20	0.30	0.30	0.30	0.30	0.30	0.30
-20.8	888.	888.	888.		112.	103.	109.	108.	104.	107.
888.0	888.	888.	888.		203.	212.	206.	207.	211.	208.
831700920	0.00	366	25	32	0.28	0.30	0.29	0.28	0.30	0.29
-17.9	888.	888.	888.		107.	97.	104.	99.	103.	102.
888.0	888.	888.	888.		234.	244.	237.	242.	238.	239.
831700940	0.00	393	29	29	0.30	0.31	0.31	0.30	0.32	0.31
-23.7	888.	888.	888.		100.	108.	104.	97.	120.	106.
888.0	888.	888.	888.		264.	256.	260.	267.	244.	258.
831701000	0.00	418	34	33	0.28	0.27	0.28	0.28	0.27	0.27
-19.5	888.	888.	888.		103.	105.	103.	99.	105.	101.
888.0	888.	888.	888.		281.	279.	281.	285.	279.	283.
831701020	0.00	442	40	39	0.31	0.33	0.32	0.31	0.33	0.32
-20.6	888.	888.	888.		134.	130.	134.	130.	137.	134.
888.0	888.	888.	888.		268.	272.	268.	272.	265.	268.
831701040	0.00	458	46	30	0.26	0.22	0.24	0.26	0.23	0.24
-15.2	888.	888.	888.		101.	107.	102.	97.	114.	102.
888.0	888.	888.	888.		311.	305.	310.	315.	298.	310.
831701100	0.00	473	51	29	0.24	0.26	0.25	0.24	0.27	0.25
-11.4	888.	888.	888.		113.	105.	110.	105.	118.	110.
888.0	888.	888.	888.		309.	317.	312.	317.	304.	312.
831701120	0.00	489	54	17	0.27	0.25	0.26	0.27	0.25	0.26
-15.9	888.	888.	888.		116.	106.	112.	116.	113.	114.
888.0	888.	888.	888.		319.	329.	323.	319.	322.	321.
831701140	0.00	500	58	27	0.28	0.29	0.29	0.28	0.30	0.29
-17.3	888.	888.	888.		112.	107.	110.	108.	132.	118.
888.0	888.	888.	888.		330.	335.	332.	334.	310.	324.
831701200	0.00	503	61	18	0.27	0.29	0.28	0.27	0.29	0.28
-16.3	888.	888.	888.		111.	107.	111.	108.	120.	113.
888.0	888.	888.	888.		331.	335.	331.	334.	322.	329.
831701220	0.00	509	65	18	0.29	0.27	0.28	0.29	0.27	0.28
-17.7	888.	888.	888.		119.	96.	110.	119.	102.	112.
888.0	888.	888.	888.		325.	348.	334.	325.	342.	332.
831701240	0.00	514	64	5	0.34	0.36	0.35	0.34	0.36	0.35
-31.1	888.	888.	888.		108.	139.	121.	116.	133.	123.
888.0	888.	888.	888.		342.	311.	329.	334.	317.	327.
831701300	0.00	516	64	-1	0.32	0.35	0.34	0.32	0.35	0.34
-22.9	888.	888.	888.		125.	133.	129.	129.	139.	134.
888.0	888.	888.	888.		327.	319.	323.	323.	313.	318.
831701320	0.00	508	64	29	0.34	0.34	0.34	0.35	0.33	0.34
-31.8	888.	888.	888.		113.	154.	127.	124.	148.	132.
888.0	888.	888.	888.		331.	290.	317.	320.	296.	312.
831701340	0.00	496	63	9	0.31	0.32	0.32	0.32	0.32	0.32
-28.9	888.	888.	888.		96.	122.	106.	106.	116.	110.
888.0	888.	888.	888.		337.	311.	327.	327.	317.	323.
831701400	0.00	477	63	9	0.29	0.33	0.31	0.29	0.33	0.31
-21.5	888.	888.	888.		97.	116.	105.	101.	122.	110.
888.0	888.	888.	888.		317.	298.	309.	313.	292.	304.
831701420	0.00	457	61	-4	0.30	0.32	0.31	0.30	0.32	0.31
-24.7	888.	888.	888.		94.	99.	97.	98.	104.	101.
888.0	888.	888.	888.		302.	297.	299.	298.	292.	295.

In table 4.2 are recorded results of the 24th of June, when wet-bulb temperature were measured. So there is no results for U*5,U*6,U*7,H5,H6,H7, EH5,EH6,EH7(written as 888). It can be seen on this example that the Bowen ratio method fails sometimes at night or during sunrise.

TABLE 4.2.:Results of the 24th of june 1983,from 4h20 to 7h40.

DATE	RAIN	Rn	G	WD	U*1	U*2	U*3	U*5	U*6	U*7
DL1	E1	E2	E3		H1	H2	H3	H5	H6	H7
BETA1	EB1	EB2	EB3		EV1	EV2	EV3	EV5	EV6	EV7
831750420	0.00	-15	-11	218	0.02	0.02	0.02	8.88	8.88	8.88
0.6	0.	1.	-1.		-2.	-2.	-2.	888.	888.	888.
4.7	-1.	999.	999.		-2.	-2.	-2.	888.	888.	888.
831750440	0.00	-12	-9	239	0.04	0.05	0.04	8.88	8.88	8.88
1.9	1.	2.	-1.		-3.	-3.	-3.	888.	888.	888.
999.0	999.	999.	999.		0.	0.	0.	888.	888.	888.
831750500	0.00	-3	-7	250	0.04	0.04	0.04	8.88	8.88	8.88
3.6	0.	0.	-1.		-2.	-2.	-2.	888.	888.	888.
999.0	999.	999.	999.		6.	6.	6.	888.	888.	888.
831750520	0.00	1	-5	303	0.04	0.04	0.04	8.88	8.88	8.88
2.5	1.	2.	0.		-2.	-2.	-2.	888.	888.	888.
999.0	999.	999.	999.		8.	8.	8.	888.	888.	888.
831750540	0.00	7	-2	366	0.10	0.03	0.04	8.88	8.88	8.88
11.3	7.	1.	0.		-7.	-1.	-2.	888.	888.	888.
1000.0	0.	999.	999.		16.	10.	11.	888.	888.	888.
831750600	0.00	11	0	48	0.09	.04	0.06	8.88	8.88	8.88
14.6	8.	2.	1.		-5.	-1.	-2.	888.	888.	888.
999.0	999.	999.	999.		16.	12.	13.	888.	888.	888.
831750620	0.00	11	0	104	0.12	0.04	0.06	8.88	8.88	8.88
18.0	14.	2.	1.		-9.	-1.	-2.	888.	888.	888.
999.0	999.	999.	999.		20.	12.	13.	888.	888.	888.
831750640	0.00	33	2	150	0.03	0.03	0.03	8.88	8.88	8.88
5.5	4.	4.	2.		-1.	-1.	-1.	888.	888.	888.
-0.3	42.	42.	42.		32.	32.	32.	888.	888.	888.
831750700	0.00	38	4	201	0.08	0.08	0.08	8.88	8.88	8.88
22.1	11.	9.	5.		-2.	-2.	-2.	888.	888.	888.
-0.2	42.	44.	43.		36.	36.	36.	888.	888.	888.
831750720	0.00	83	6	213	0.09	0.10	0.11	8.88	8.88	8.88
-53.1	18.	17.	14.		1.	-1.	0.	888.	888.	888.
0.1	73.	82.	77.		76.	78.	77.	888.	888.	888.
831750740	0.00	155	11	230	0.12	0.13	0.13	8.88	8.88	8.88
-13.3	56.	74.	51.		12.	8.	11.	888.	888.	888.
0.2	119.	130.	124.		132.	136.	133.	888.	888.	888.

From these 20-min data, the mean values over the daylight period (8h00-18h00) and over the whole day are calculated, when no value is missing. For the Bowen ratio method, no daily data can be obtained since this method fails sometimes. The daily data of the actual evapotranspiration calculated by the direct method are not numerous but they are more numerous for the indirect method and this enables later a comparison with the results derived from the advection-aridity method or with the potential evapotranspiration. The averaged values on three consecutive days are also calculated for the latter analysis.

4.2. Potential evapotranspiration and actual evapotranspiration calculated by the advection-aridity method

4.2.1. The applied formulations:

All the terms are defined as before and in the same units.

4.2.1.1. Penman's formulation:

Penman's formula is

$$ETPE = \frac{s}{s+\gamma}(Rn-G) + \frac{\gamma}{s+\gamma}\cdot f(u)\cdot\overline{\Delta e} \qquad (4.28)$$

ETPE, Rn and G are in W/m2 and are mean daily values;

The wind function chosen here is the 'weak' one: $f(u)=0.26.(0.5+0.54.u)$ where u is, in m/s, the mean wind speed at about 2m height. This formula gives the evapotranspiration in mm/day and to get it in W/m2, it has to be multiplied by 28.5.

4.2.1.2. The formulation of Thom and Oliver:

This formulation is written as:

$$ETTO = \frac{s}{s+\gamma(1+n)}(Rn-G) + \frac{m\gamma}{s+\gamma(1+n)} f(u)\cdot\overline{\Delta e} \qquad (4.29)$$

n is the ratio of the canopy resistance (rc) to the aerodynamic resistance. rc is taken as 65 s/m and ra is defined by the following formula:

$$ra = 4.72\left[\ln\left(\frac{z}{zo}\right)\right]^2/f(u) \qquad (4.30)$$

m is the ratio of the aerodynamic resistance of water as expressed by Penman to the aerodynamic resistance over grass surface:

$$m=\left[\frac{\ln(z/zo)}{\ln(z/zop)}\right]^2 \quad \text{with } z=2.00m, zo=0.01m \text{ and } zop=0.00137m \quad : m=1.9$$

f(u) is the strong function: $f(u)=0.26(1+0.54.u)$.

The formulations of Penman and of Thom and Oliver can be used during the whole year.

4.2.1.3. The formulation of Priestley and Taylor:

The formulation of Priestley and Taylor

$$ETPT = 1.28\frac{s}{s+\gamma}(Rn-G) \qquad (4.31)$$

The expression is only used during the growing season, from April to September. Outside this period, the evapotranspiration is mainly determined by large-scale advection conditions and less by radiation.

4.2.1.4. The formulations of Makkink:

There are two ways of expressing Makkink's formula:

-excluding the soil heat flux:

$$ETM1 = 0.65 \frac{s}{s + \gamma} Rg \qquad (4.32)$$

Rg is the incoming short-wave radiation or global radiation, in W/m2.
This is the standard formulation.

-including the soil feat flux:

$$ETM2 = 0.65 \left(\frac{s}{s + \gamma}\right) (Rg - 2G) \qquad (4.33)$$

The two formulations can be employed during the whole year, but for the winter period, the figures become more uncertain.

4.2.1.5. Calculations of the water vapour deficit:

s is by definition des/dT, where es is the saturation pressure of water vapour. es is calculated from the Clapeyron's formula, expressed in section 4.1.2.1.

$$es = 1.333.(aa + as.T + at.T + au.T + av.T) \qquad (4.34)$$

es is in mbar. The value of aa is 4.58.

Δe is the water vapour deficit in the air: $\Delta e = es - e$ with e as the water vapour pressure in the air. The relative humidity is defined by RH = e/es. It can be expressed by RH = 1 - e/es. And Δe can be calculated from the relative humidity with the following relation:

$$\Delta e = es.(1 - RH) \qquad (4.35)$$

4.2.1.6. The advection-aridity method:

For the period going from May to August, the actual evapotranspiration can be calculated by the advection-aridity method, using the results of the potential evapotranspiration. According to the conditions of application described by Brutsaert and Stricker of the advection-aridity method, three formulations can be employed:

-ETA1 = 2.ETPT - ETPE (4.36)
-ETA2 = 2.ETM1 - ETPE (4.37)
-ETA3 = 2.ETPT - ETTO (4.38)

4.2.2.Development of the program:

4.2.2.1.Completing the set of data:

The set of data for the period going from the 1st of January 1983 to the 31st of October 1984 is not complete.Nevertheless,the calculation has to be done for every day,in order to calculate the water balance.The data which are required are the mean daily values of the net radiation,global radiation and soil heat fluxes in W/m2,of the wind speed at 2m height in m/s,of the air temperature(dry-bulb) at 2m height in K,and,for the calculation of the water vapour deficit in the air,the value of the relative humidity.The mean daily values were calculated from the 20-min data,if available.Otherwise,daily values were taken from the meteorological station in Wageningen,either measured values,either corrected value,according to the results of the correlation analysis.

-Net radiation:The analysis on the monthly values yields good results so the same value as in Wageningen was adopted.Figure 4.1. shows the scatter diagram and the results of the correlation study.For some days,values are missing in both stations.In that case,the net radiation has been calculated from global radiation,according to the linear relationship found between these two components for the period from the 15th of May to 15th of June in 1983.See figure 4.2. for the scatter diagram and the numerical results.

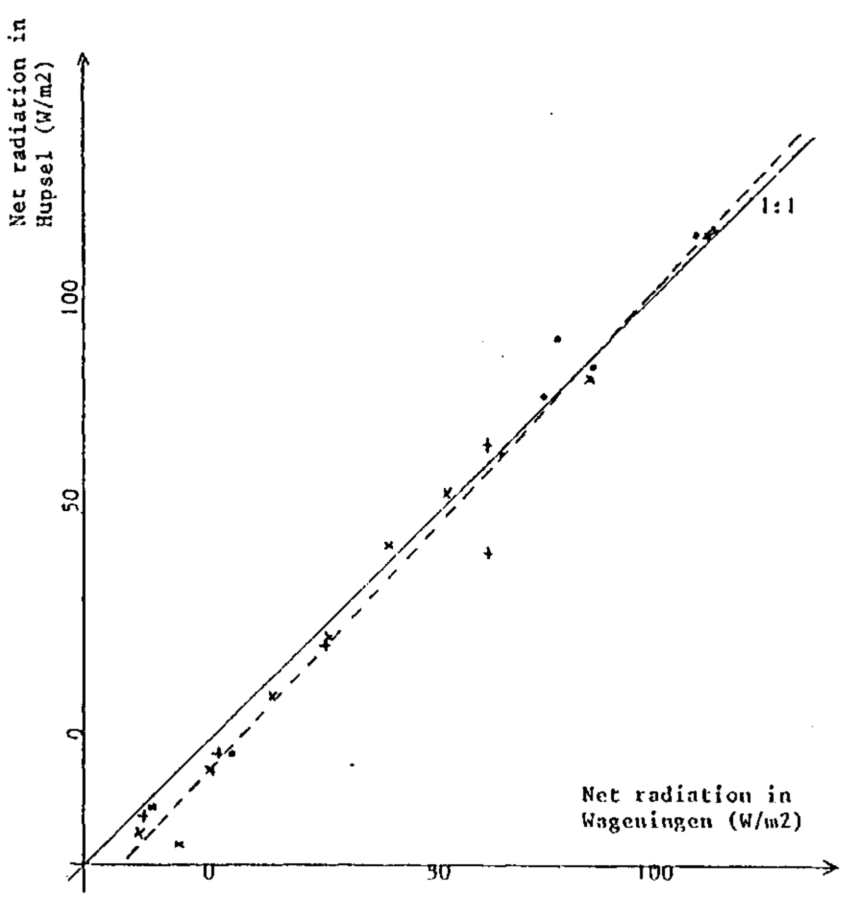


FIGURE 4.1.:Comparison of the net radiation in Hupselse Beek catchment and in Wageningen,monthly values:

:1983;+:January to May 1984;.: June to October 1984

- - -:best straight line:Rnh=1.08 Rnw - 7.15
coefficient of correlation :0.99

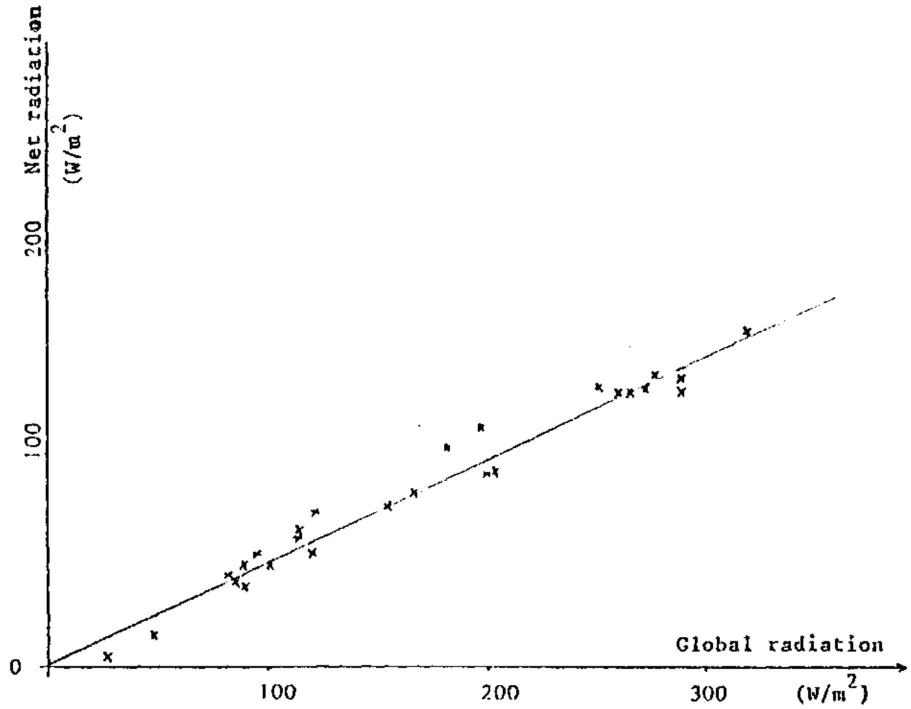


FIGURE 4.2.: Relation between the net radiation and
the global radiation in Hupsel catchment
———:best straight line:Rn=0.48 Rg + 2
Coefficient of correlation :0.98

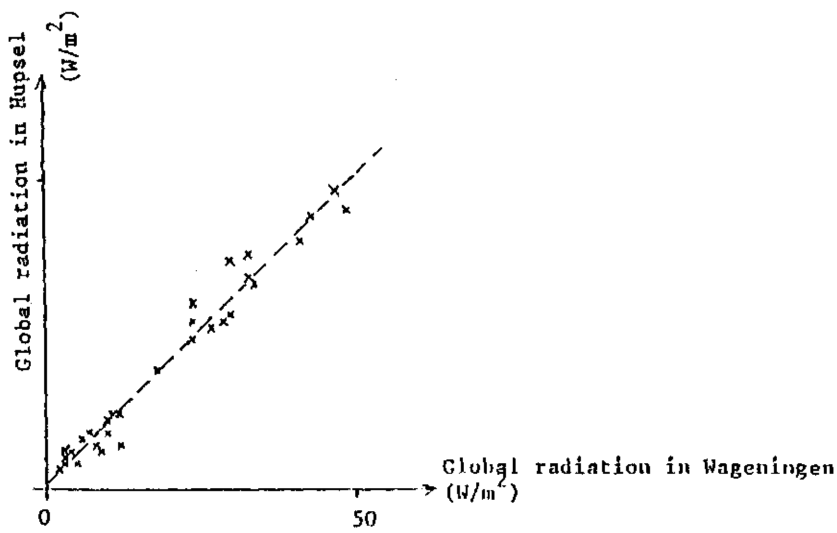


FIGURE 4.3.:Comparison of the global radiation in Hupsel
catchment and in Wageningen
Daily values of January 1983.
- - -:best straight line:Rgh = 0.99 Rgw + 0.35
Correlation coefficient: 0.98

-Global radiation:The correlation between the values measured in Hupsel (Rgh) and in Wageningen (Rgw) had been studied for January and July 1983, figures 4.3. and 4.4. are the corresponding scattered diagrams.The two best straight lines :Rgh=0.99 Rgw+0.35 in January and Rgh=1.00 Rgw+2.55 in July and the good coefficients of correlation allow to take the measured value in Wageningen as an estimate of the value in Hupsel.

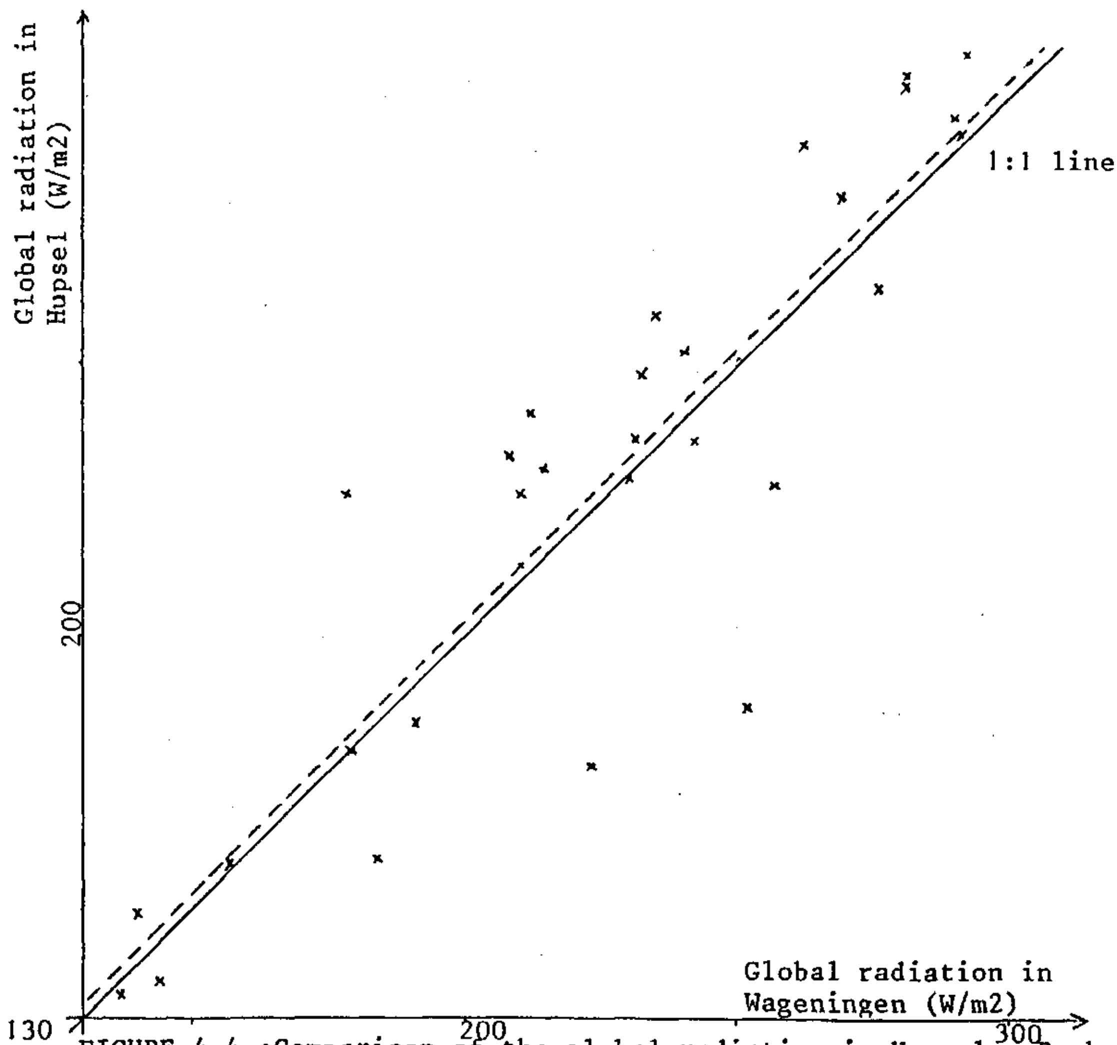


FIGURE 4.4.:Comparison of the global radiation in Hupselse Beek catchment and in Wageningen, daily values of July 83

- - -: best straight line:Rgh=1.00 Rgw + 2.55
coefficient of correlation :0.89

-Soil heat flux:This component is not measured in Wageningen.For all the available mean daily data,the multilinear relationship between the soil heat flux,the temperature and the net radiation was studied.The result is the equation:G=0.4 T +0.08 Rn -4.6 (G and Rn are in W/m2 and T in °C).The coefficient of correlation is 0.7.This relation was thus taken.

-Wind speed:The linear relationship found between the values measured in the two stations (uh and uw,in m/s) is far from the 1:1 relationship. It was found as a best fit :uh=0.72 uw +1.1,with a correlation of 0.94. Figure 4.5.represents the scatter diagram for these two variables.The values taken to complete the data were calculated from the values in Wageningen through this formula.

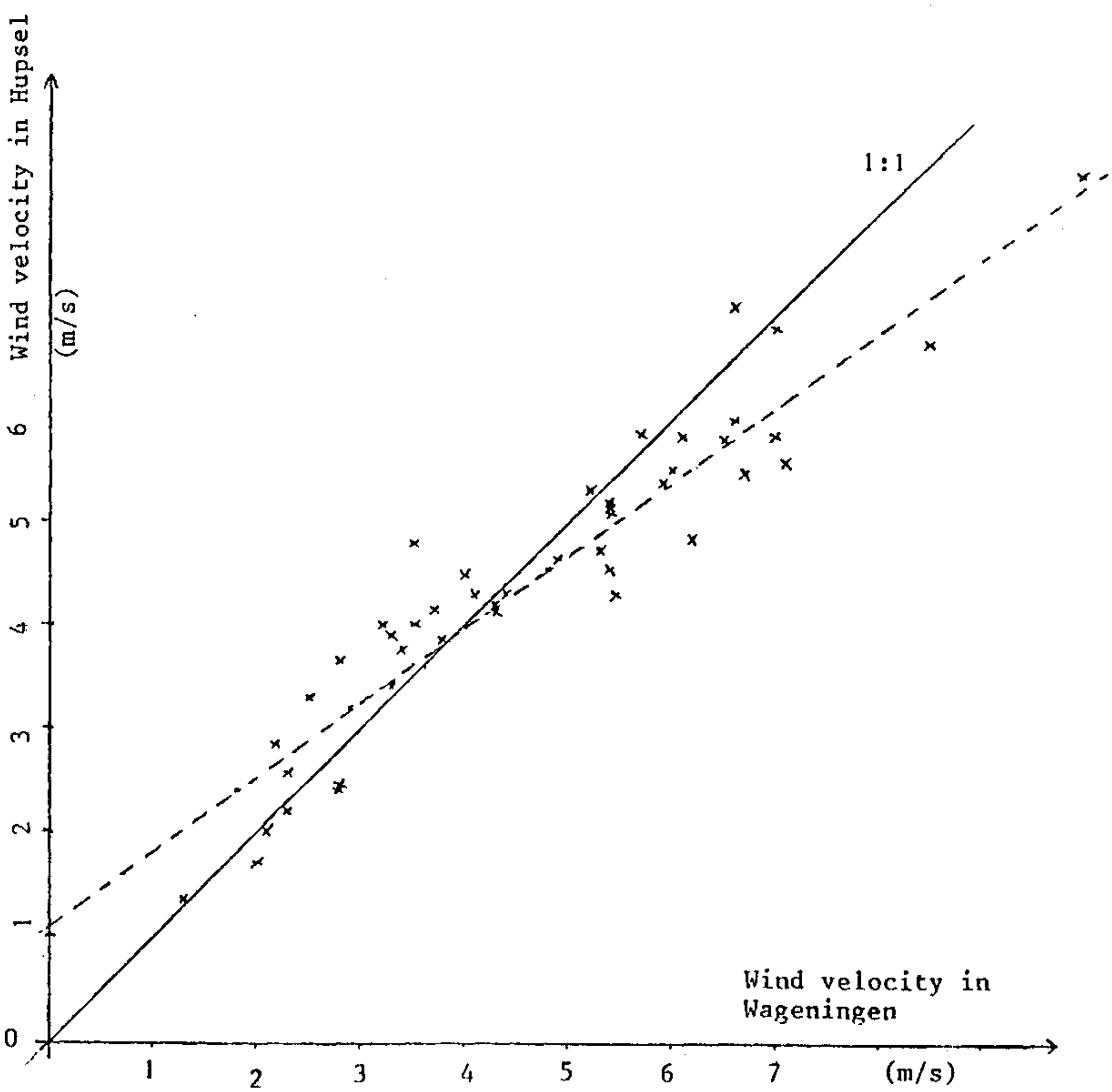


FIGURE 4.5.: Comparison of the wind velocity in Hupsel catchment and in Wageningen

- - -:best straight line:uh=uw.0.72 + 1.10

Coefficient of correlation: 0.94

-Air temperature:No important difference was noted between both stations since the relation is:Th=0.99 Tw +0.05 (for temperatures expressed in ^0C),with a correlation coefficient of 0.99.So there is no problem in taking values measured in Wageningen to complete the set of data.Figure 4.6.is the corresponding diagram.

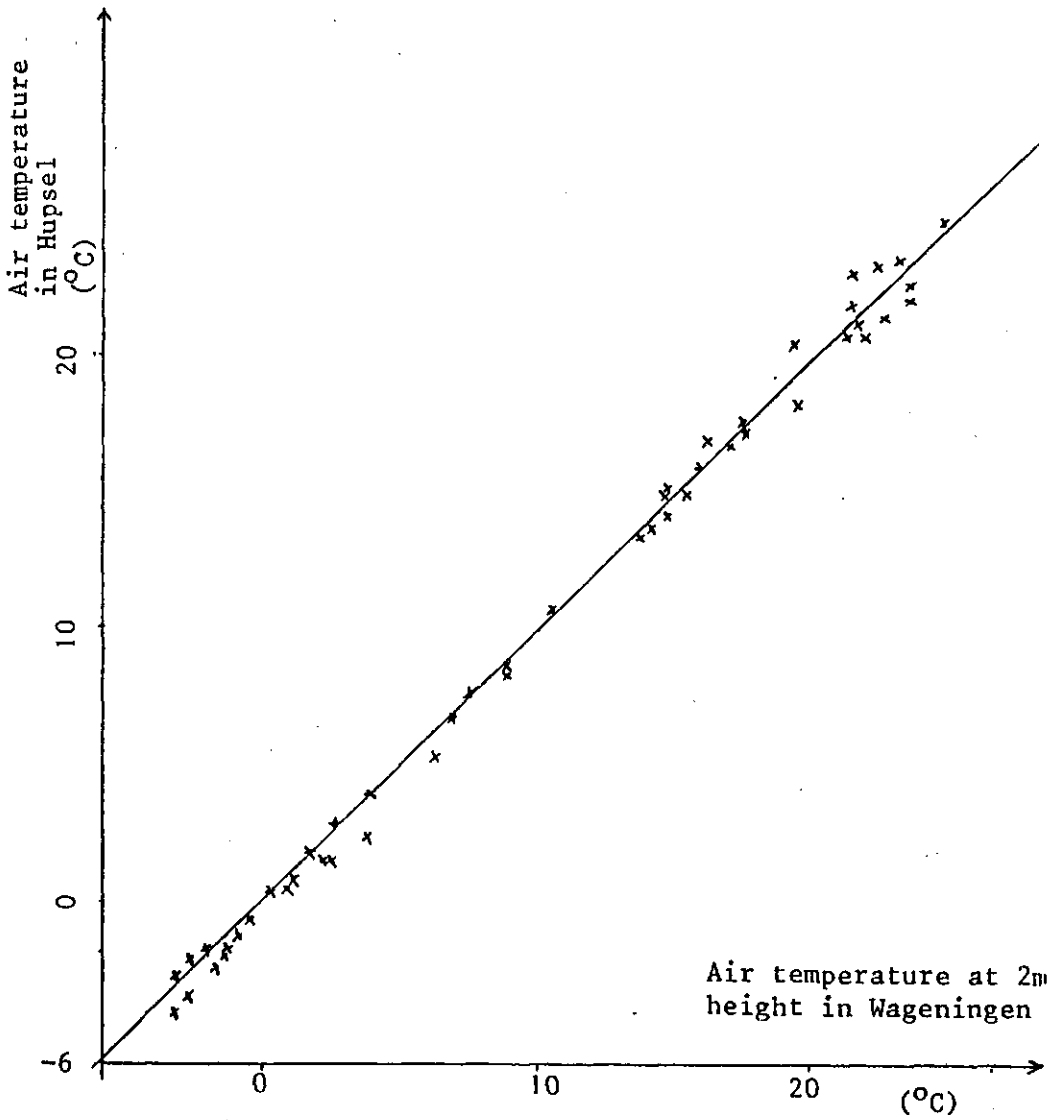


FIGURE 4.6.: Comparison of the air temperature in Hupsel catchment and in Wageningen

——:best straight line:Th =0.99 Tw + 0.05

Coefficient of correlation: 0.99

-Water vapour deficit:In Wageningen,the values of the water vapour deficit are recorded.For 50 days when the mean values in Hupsel were calculated,they were compared to the values in Wageningen and the relationship is DEh =1.01 DEw + 0.23,for a coefficient of correlation of 0.96.See figure 4.7.So that the values in Wageningen are acceptable.

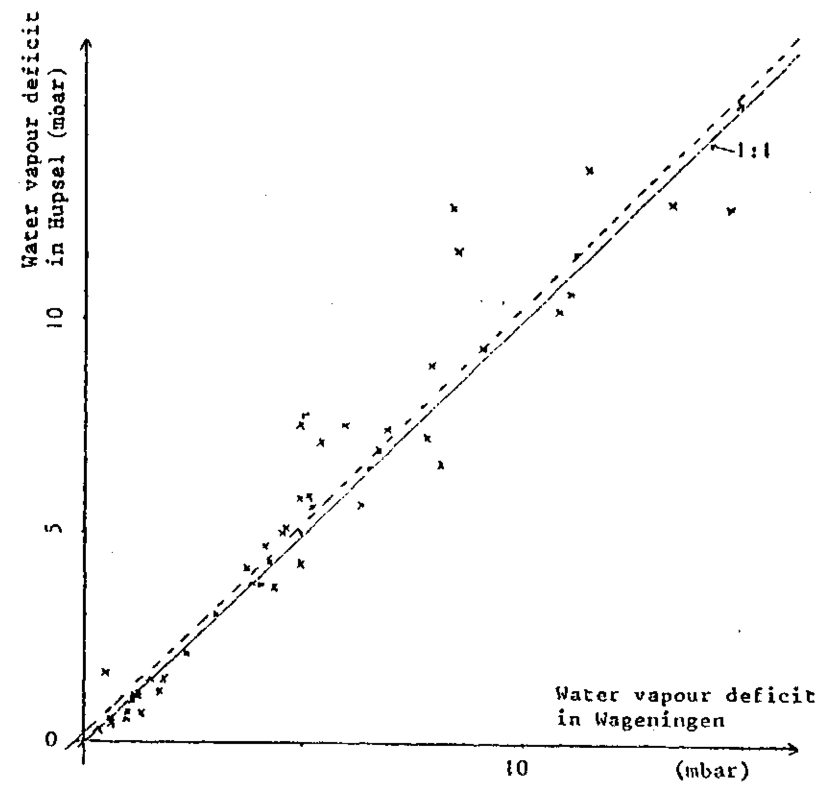


FIGURE 4.7.: Comparison of the water vapour deficit
in Hupsel catchment and in Wageningen
- - - :best straight line:DEh=1.01 DEw +0.23
Coefficient of correlation: 0.96

The results of potential evapotranspiration,computed with some completed data from Wageningen are only used for the water balance calculations.The analysis,given in chapter 5,strictly apply to results from data measured in Hupsel catchment.

4.2.2.2.Calculations and results:

When the mean daily values are calculated,the formulations (4.28),(4.29),(4.31),(4.32),(4.33) are used to compute the potential evapotranspiration.Then,the results are used in the formulas (4.36),(4.37) and (4.38) to calculate the actual evapotranspiration by the advection-aridity method.

These calculations were executed in the program POTEVA which listing is given in appendix.

Table 4.3. shows as an example the results of the month of July 1983.

TABLE 4.3.:Potential evapotranspiration and actual evpotranspiration
---------- calculated by the advection-aridity method (in W/m2)
in the month of July 1983.

Potential evapotranspiration:
- -ETPE : From Penman
- -ETTO : From Thom and Oliver
- -ETPT : From Priestley and Taylor
- -ETM1 and ETM2 : From Makkink

Actual evapotranspiration from the advection-aridity method:ETA1,ETA2,ETA3

DAY	ETPE	ETTO	ETPT	ETM1	ETM2	ETA1	ETA2	ETA3
83182	82.08	77.58	80.57	90.87	83.79	79.05	99.66	83.55
83183	74.42	76.20	65.14	65.33	60.37	55.85	56.23	54.08
83184	95.00	97.52	97.20	111.37	96.19	99.40	127.75	96.88
83185	107.69	112.27	111.57	128.65	114.17	115.46	149.62	110.87
83186	140.41	151.26	122.79	139.16	124.71	105.16	137.92	94.31
83187	72.97	82.97	64.95	83.14	72.29	56.94	93.31	46.94
83188	97.42	104.28	98.25	110.31	92.92	99.08	123.21	92.22
83189	102.95	110.49	100.09	115.97	98.42	97.23	129.00	89.68
83190	96.55	104.84	90.71	108.71	93.04	84.87	120.86	76.57
83191	125.65	148.84	112.91	137.89	118.94	100.16	150.12	76.97
83192	134.00	160.15	119.54	135.38	117.07	105.07	136.75	78.93
83193	142.43	155.99	126.18	139.45	124.38	109.92	136.47	96.36
83194	83.01	79.49	72.82	73.96	71.44	62.63	64.91	66.15
83195	77.57	83.56	71.65	77.32	72.36	65.74	77.07	59.75
83196	112.58	123.16	97.55	106.28	97.27	82.52	99.98	71.94
83197	103.20	116.59	94.29	115.29	100.42	85.38	127.38	71.99
83198	123.37	141.60	102.38	120.22	105.37	81.38	117.08	63.16
83199	103.47	108.27	95.20	103.47	95.34	86.94	103.47	82.14
83200	76.31	75.61	72.56	75.81	70.73	68.81	75.31	69.51
83201	102.47	102.14	89.51	90.11	88.52	76.55	77.75	76.88
83202	108.17	110.70	107.33	116.57	112.59	106.49	124.96	103.96
83203	131.94	145.49	117.10	132.93	123.31	102.27	133.91	88.72
83204	99.38	116.03	80.34	96.56	86.58	61.30	93.73	44.65
83205	54.02	57.41	52.13	65.73	57.79	50.23	77.45	46.84
83206	89.92	95.45	93.05	101.64	89.16	96.19	113.36	90.65
83207	113.44	126.84	97.91	107.42	96.16	82.39	101.40	68.98
83208	53.40	58.85	48.82	60.65	54.45	44.25	67.91	38.79
83209	66.94	68.98	55.90	57.63	53.33	44.85	48.32	42.81
* 83210	72.84	79.12	62.85	64.23	60.19	50.66	53.39	44.39
83211	101.67	107.06	101.29	110.78	101.99	100.90	119.89	95.51
83212	114.15	140.08	94.77	107.82	97.64	75.40	101.50	49.47

* means that the data of this day had been completed with data from Wageningen

CHAPTER 5:ANALYSIS

The results have to be analysed on two levels:
1)The sensitivity of the results to the different components.
2)The comparison of the results,obtained for different levels or by different methods,of actual and potential evapotranspiration.

Foreword:

Some strange values appear now and then in the results.Some of them can be explained by an odd datum.As an example,on the 20th of June 1983,at 8h40,the values of EH1,EH2,EH3 are 207,201,204 W/m2 and for EH5,EH6,EH7: 169,-192,57 W/m2.This occurs immediatly after a period when the temperature differences were not measured.The value of W73 is then -7.1 ^{0}C when D73 is -2.5 ^{0}C,the usual difference between these two measurements is only a few hundredthes of degree.W73 intervenes in H6 and H7,this wrong datum is the origin of this inconsistent result.This happens a few times after a period with missing measurements.

But often,no explanation can be found in the set of data.A problem during the iteration procedure may be the source of these strange values.

5.1.Sensitivity analysis:

The sensitivity analysis is generally made on a period of five days (from the 14th to 19th of July 1983),when the wet-bulb temperatures were measured in order to have data for all the methods.The analysis has been done on 20-min data.Results are given either for 20-min interval,either for daylight data(average calculated over the period 8h00-18h00).Remaining data were not used here because the results of the Bowen ratio method may not be reliable for periods outside the daylight period.

5.1.1.Sensitivity to the choice of roughness parameter and zero-displacement height:

The roughness parameters do and zo are difficult to determine with precision.The reasons for this are that they are depending on the wind direction and varying with time,as they are directly linked to the height of the grass.In accordance with the rule expressed by the formulas (3.9), the values zo=0.01m and do=0.05m(case 1) had been chosen.Nevertheless,some calculations have also been done with other values:zo=0.005m and do=0.025m (case 2);zo=0.015m and do=0.075m (case 3),which represents 50% less and 50% more than the values employed and corresponds to a crop height of respectively 0.05 and 0.15m.

The value of zo is only used when the wind velocity at 3.97m above the soil surface is smaller than 1.50m/s.Among the set of 20-min data, eighty were satisfying this condition,but some are measurements taken outside the daylight period.

The mean values of u*,H,E and EH are reported in table 5.1 as well as the ratio of the value obtained in case 2 or 3 to the value obtained in case 1.

TABLE 5.1:Influence of the choice of the roughness parameter zo and --------- the zero-displacement height do:

	Case 1: zo=0.01m do=0.05m	Case 2: zo=0.005m do=0.025m		Case 3: zo=0.015m do=0.075m	
			Ratio		Ratio
u*1(m/s)	0.053	0.048	0.91	0.056	1.06
u*2(m/s)	0.058	0.052	0.90	0.063	1.09
u*3(m/s)	0.056	0.050	0.89	0.060	1.07
H1(W/m2)	7.16	8.09	1.13	6.51	0.91
H2(W/m2)	15.58	17.54	1.13	14.49	0.93
H3(W/m2)	9.50	10.81	1.14	8.72	0.92
E1(W/m2)	22.85	24.81	1.09	21.56	0.94
E2(W/m2)	33.84	36.74	1.09	32.24	0.95
E3(W/m2)	23.76	26.14	1.10	22.24	0.94
EH1(W/m2)	37.33	36.40	0.98	37.98	1.02
EH2(W/m2)	28.91	26.95	0.93	30.00	1.04
EH3(W/m2)	34.99	33.68	0.96	35.76	1.02

Both parameters have no influence on the Bowen ratio.

It can be seen that the influence on u* is in a range from 6 to 10%, a rougher surface yields a higher u*.On the sensible heat flux,the variation is from 8 to 14%,and a rougher surface implies a decrease in heat transfer.The evapotranspiration (EH) calculated from the energy balance and the sensible heat flux is thus decreasing;but the variation in comparison with the basic values is only of a few percents(2 to 4%),due to higher absolute values here.The influence on the results of the direct method (E) is in the same order (6 to 10%) as it was on the heat transfer.

No definite conclusion can be drawn from this,since this sample is not restricted to daylight values.

5.1.2.Sensitivity of the formulation of the Monin-Obukhov stability length

As pointed out in section 3.2.4.2.,the effect of buoyancy due to the specific humidity gradient was not taken into account in the original definition of the Monin-Obukhov length and even now it is not often included.The calculations were done without the complete formulation (3.16) but with the incomplete one (4.3).

Calculations of the friction velocity and of the sensible heat flux with the complete formulations had been made for two periods: a wet (mid May 1983) and a dry (mid July 1983).In table 5.2.are presented some of these results.

The results had to be written with a very high precision,6 decimales.

TABLE 5.2:Influence of the formulation of the Monin-Obukhov length

With the complete formulation		With the incomplete formulation	
H1(W/m2)	L1(m)	H1(W/m2)	L1(m)
-26.189193	14.179715	-26.189240	14.179727
-18.669448	10.199947	-18.669444	10.199946
-23.803627	11.363874	-23.803879	11.363890
-39.183899	22.370597	-39.183902	22.370599
-29.692891	17.449271	-29.692870	17.449277
43.441170	-60.088735	43.441182	-60.088723
76.134598	-39.841410	76.134622	-39.841431
83.134603	-50.225526	83.134561	-50.225520
-1.067188	0.806487	-1.067187	0.806486
-2.078884	0.587526	-2.078885	0.587526

The conclusion is that values of H and thus of EH and of E are insensitive to the exact formulation.

5.1.3.Sensitivity to the wind velocity:

The error usually made on wind velocity is an overestimate. Calculations have been done with errors of -10% and +10% on u.The results are in table 5.3.
The influence of these errors are of importance to u* with a deviation between 7 and 10 percents.For heat and vapour transfers,the influence is of minor importance , between 1 and 3 percents for H and E and by consequence less than 1 percent on EH.It may be concluded that errors on the wind velocity do not affect the results of evapotranspiration very much.

From the results of table 5.1.,it was seen that a decrease in u* implies an increase in H and E,and that is the contrary in the results of table 5.3.This is not surprising since the sample are not the same and the results are thus not comparable.

5.1.4.Sensitivity to net radiation and soil heat flux:

Also in table 5.3.the results are presented of the sensitivity of the fluxes with respect to the inaccuracies in Rn and G.

In the formulation of the evaporation from the indirect method ($EH = Rn - G - H$),the influence of the net radiation is more important than in the formulation of the evaporation from the Bowen ratio ($EB = (Rn - G) / (1+\beta)$).A variation of 10% of the net radiation leads to a variation in the same direction of about 27% for the indirect method and 11% for the Bowen ratio method.

The net radiation is a very important component and a very high accuracy of its measurement is necessary in order to get accurate data of the evapotranspiration,especially if the indirect method is used.

Since the order of magnitude of the soil heat flux is usually small as compared to the other components of the energy balance,its influence on the results of evaporation is very small:about 3% for the indirect method and 1 to 2% for the Bowen ratio method.

TABLE 5.3:Influence of the wind velocity,net radiation
--------- and soil heat flux

Ratio of the mean value obtained from 5 daylight values to the value calculated with the measured data:

	u-10%	u+10%	Rn-10%	Rn+10%	G-10%	G+10%
u*1(m/s)	0.90	1.04				
u*2(m/s)	0.93	1.07				
u*3(m/s)	0.92	1.08				
H1(W/m2)	0.99	1.01				
H2(W/m2)	0.99	1.03				
H3(W/m2)	0.99	1.01				
E1(W/m2)	0.97	1.03				
E2(W/m2)	0.99	1.02				
E3(W/m2)	0.99	1.02				
EB1(W/m2)			0.89	1.11	1.02	0.99
EB2(W/m2)			0.89	1.11	1.01	0.99
EB3(W/m2)			0.89	1.11	1.01	0.99
EH1(W/m2)	1.00	1.00	0.74	1.28	1.03	0.97
EH2(W/m2)	0.99	1.00	0.74	1.28	1.03	0.98
EH3(W/m2)	1.00	1.00	0.74	1.28	1.03	0.98

(u+10% means that the measured value of u has been increased by 10% for this calculation.)

5.1.5.Sensitivity to temperature differences:

The sensitivity of the dry-bulb temperature differences and of the wet-bulb temperature differences,separatly or together has been analysed by making the calculations with some systematic errors:

+0.05^{0}K or -0.05^{0}k on all temperature differences.

+0.01^0 K,+0.03 ^{0}K,+0.05 ^{0}K,-0.01 ^{0}K,-0.03^{0}K,-0.05^0 K on either the dry-bulb temperature differences or the wet-bulb temperature differences.

The mean daylight values of 5 days,calculated from the originally measured 20-min data have been related to values calculated by the error included,measured data.

Results are shown in table 5.4.

TABLE 5.4: Influence of the temperature differences measurements:

Ratio of the mean value obtained from 5 daylight values to the value calculated from the measured data:

	ΔT-0.05 *	ΔT+0.05	ΔTd-0.01	ΔTd-0.03	ΔTd-0.05	ΔTd+0.01	ΔTd+0.03	ΔTd+0.05	ΔTw-0.01	ΔTw-0.03	ΔTw-0.05	ΔTw+0.01	ΔTw+0.03	ΔTw+0.05
u*1(m/s)	0.95	1.00	0.95	0.95	1.00	1.00	1.00	1.00						
u*2(m/s)	0.93	1.04	1.00	0.96	1.04	1.00	1.04	1.04						
u*3(m/s)	1.00	1.04	1.00	1.00	1.04	1.00	1.04	1.04						
H1(W/m2)	0.71	1.34	0.93	0.82	0.71	1.06	1.19	1.34						
H2(W/m2)	0.56	1.57	0.90	0.72	0.56	1.10	1.33	1.57						
H3(W/m2)	0.80	1.21	0.96	0.88	0.80	1.04	1.13	1.21						
E1(W/m2)	0.75	1.26	0.83	0.65	0.42	1.13	1.39	1.78	0.95	0.86	0.77	1.04	1.14	1.23
E2(W/m2)	0.72	1.33	0.82	0.50	0.34	1.14	1.43	1.67	0.95	0.86	0.77	1.05	1.14	1.23
E3(W/m2)	0.86	1.15	0.94	0.77	0.68	1.06	1.22	1.34	0.98	0.95	0.91	1.02	1.05	1.09
EB1(W/m2)	1.04	0.98	0.98	0.95	0.92	1.02	1.05	1.08	0.99	0.97	0.94	1.01	1.03	1.04
EB2(W/m2)	1.05	0.97	0.98	0.95	0.92	1.02	1.05	1.08	0.99	0.97	0.94	1.01	1.02	1.03
EB3(W/m2)	1.02	0.99	0.98	0.98	0.96	1.10	1.02	1.04	0.99	0.98	0.97	1.00	1.01	1.02
EH1(W/m2)	1.06	0.94	1.01	1.03	1.08	0.99	0.96	0.93						
EH2(W/m2)	1.10	0.88	1.02	1.06	1.12	0.98	0.93	0.88						
EH3(W/m2)	1.04	0.96	1.01	1.02	1.05	0.99	0.98	0.96						

* : ΔT means ΔTd and ΔTw experience the same inaccuracy.

Several facts can be pointed out:

-the low sensitivity of the friction velocity:the temperature difference is not a determining factor of the friction velocity.It is only intervening indirectly in the calculation of u* by L,during the iteration process.

-the sensible heat flux is very sensitive to a deviation in the temperature (dry-bulb) differences.

-among the three methods,the direct method is the most sensitive and has a very high level of sensitivity.A systematic error of +0.03^{0}K (respectively -0.03^{0}K) on the dry-bulb temperature differences leads to an error varying from -23% to -50% (respectively +22% to +43%) .For wet-bulb temperature differences errors seems to have much less influence.The same error gives an error of less than 7% on the results calculated by the other methods.

-the global level (1.30m-7.14m) is always the least sensitive and most often the upper level(3.15m-7.14m) is the most sensitive one.
The temperature difference between 1.30m and 7.14m is the largest,and a fixed systematic error on all the temperature gradients leads thus to a relative error which is the smallest for the global level.When all sensors of the psychrometer are measuring dry-bulb temperature,two series of results are available.Figure 5.1. represents the relation between the two series (daily values) for the three levels.The relation is very good for the lower level,a little worse for the upper level and a excellent for the global level.This confirms the sensitivity of the different gradients to an error.

In the theoretical error analysis (section 4.1.4.),it was concluded that an error on the dry-bulb temperature difference has the same influence on the three methods.This seems to be in opposition to the results presented in table 5.4.But the relative error is different for every 20-min measurement and in fact nothing can be concluded here on the average of 5 days.

The calculations made by the direct method need temperature measurements done with a very good accuracy:0.01 ^{0}K for the dry-bulb temperature and up to 0.03^{0}k for the wet-bulb temperature.The two other methods and particularly the indirect method need less accuracy.This latter fact is only valid under temperate climate conditions because the sensible heat flux is a smaller part of the energy budget and an error on it propagates less on the evapotranspiration.But for a dryer climate than in the Netherlands,the sensible heat flux is an important component,which can be of the same order of magnitude or even larger than the evapotranspiration.In that case a large error on H would yield an important error on the evapotranspiration.

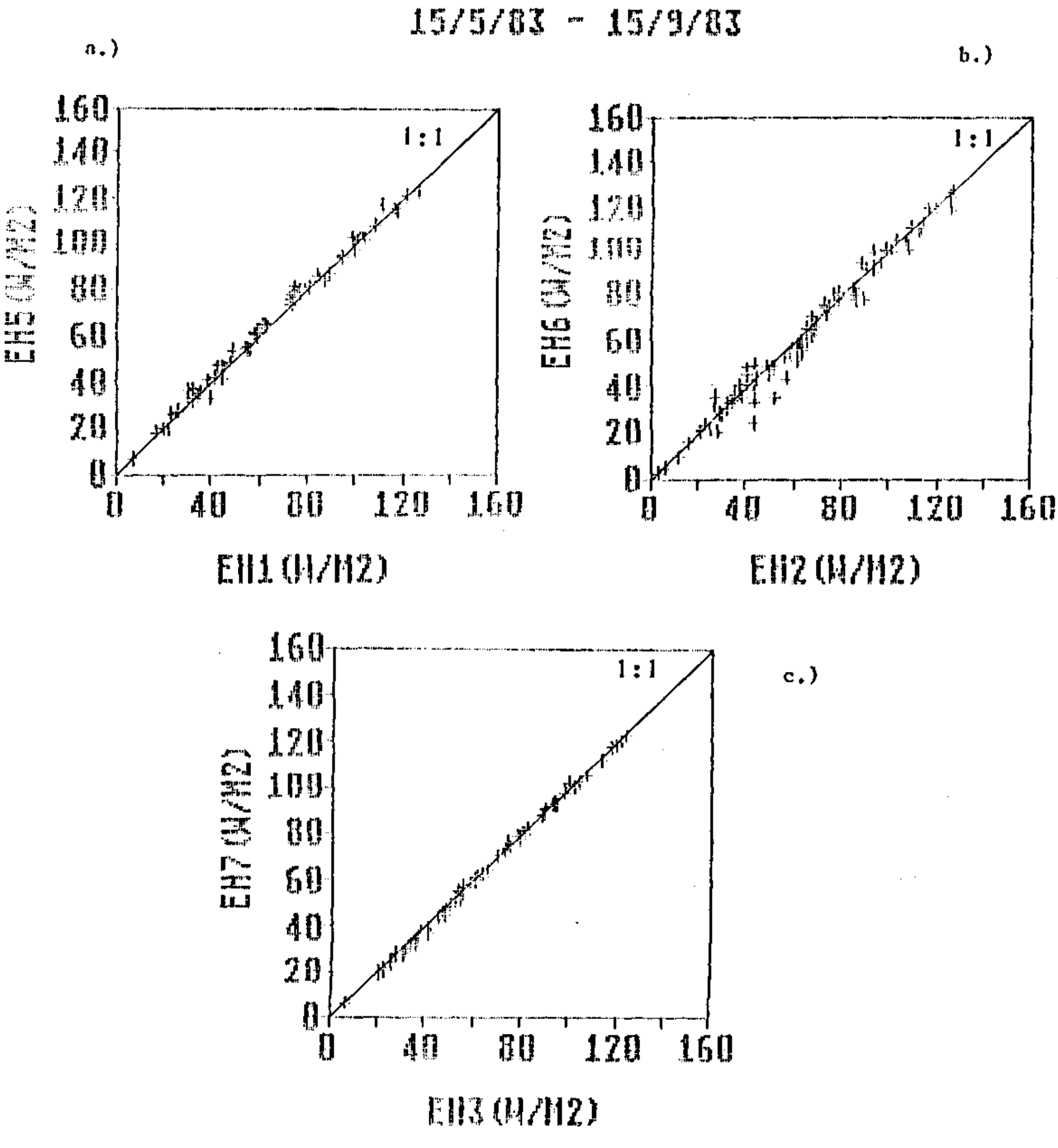


FIGURE 5.1.:Comparison of the results calculated from the two series of dry-bulb temperature gradients.Level 1.30m-3.15m (a). Level 3.15m-7.14m (b).Level 1.30m-7.14m (c). Daily values.

5.2. Comparative analysis:

5.2.1. Method:

The relationship expected between the results obtained by two different methods or from two temperature differences of different levels is always a linear relationship. For each couple of variables studied, the best straight line and the correlation coefficient are calculated by the following formulations:

-the best straight line describing the linear relationship between two variables X and Y is $Y = a.X + b$, where

$$a = \frac{\sum_{1}^{N}(x \cdot y) - N \cdot \bar{x} \cdot \bar{y}}{\sum_{1}^{N} x^2 - N\bar{x}^2} \tag{5.1}$$

$$b = \bar{y} - a \cdot \bar{x} \tag{5.2}$$

where N represents the number of elements (x,y), values taken by X and Y.
$\bar{x}$ and $\bar{y}$ are the averages of the values x and y.
a and b are the best fitted coefficients, to be estimated.

-the coefficient of correlation r is defined by the relation

$$r = \frac{\sum_{1}^{N} x \cdot y - N \cdot \bar{x} \cdot \bar{y}}{(\Sigma x^2 - N\bar{x}^2)\ (\Sigma y^2 - N\bar{y}^2)} \tag{5.3}$$

The optimal fit is obtained when a is close to 1 with a small value of b and a high value of r (close to 1).

An example of the programs used for the analysis is given in appendix(ANALYETP.FOR).

5.2.2. Actual evapotranspiration:

5.2.2.1. The friction velocity:

The study of the relation between the friction velocities calculated for wind differences at different levels gives information about the homogeneity of the atmospheric surface layer for momentum transfer to the wall or soil surface.

Table 5.5 shows the values of the coefficients of the best straight line describing the relation between the friction velocity results from the two lowest levels (u*1) and at the two highest levels (u*2), for averaged hourly values.

TABLE 5.5.:Comparison of the friction velocity
---------- at two different levels
(Hourly values, W/m2): u*2 = a.u*1 + b

	a	b	r	N
May 1983	1.09	0.04	0.809	243
Jun.1983	1.07	0.01	0.866	548
Jul.1983	1.11	0.01	0.910	692
Aug.1983	1.05	0.02	0.911	658
Sep.1983	1.42	0.02	0.927	708
Oct.1983	1.50	0.04	0.859	660
May to Oct.1983	1.26	0.02	0.859	3509
Jun.1984	1.10	0.00	0.901	546
Jul.1984	0.88	0.01	0.946	159
Aug.1984	1.21	0.00	0.892	372
Sep.1984	1.41	0.00	0.930	685
Jun. to Sep.1984	1.20	0.00	0.896	1762

Except in July 1984, u*2 is always larger than u*1 and generally directly proportional to it (b $\approx$ 0). Figure 5.2. is representing u*2 versus u*1 for some mean hourly values. An analysis on daily and daylight values leads to the same conclusion.

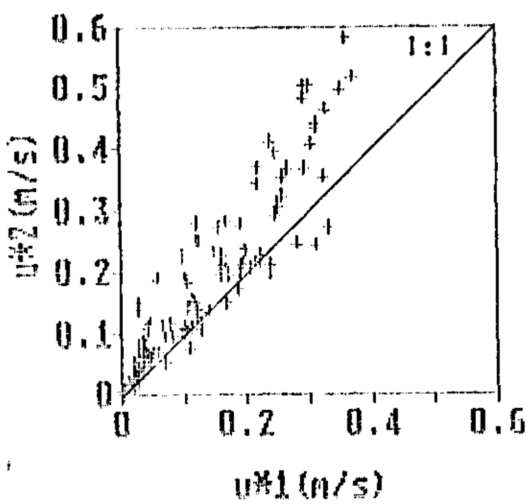


FIGURE 5.2.:Relationship between the mean values over one hour of the
---------- friction velocity for the levels 1.30m-3.15m(u*1) and 3.15m-7.14m(u*2)

What is important is that the layer is not very homogeneous since there is a mean difference of about 20% in the friction velocity calculated for the levels 1.30m-3.15m (u*1) and for the levels 3.15m-7.14m (u*2).How this fact has consequences for the heat and vapour fluxes at different heights will be seen in the next section.

u*-relationships are not analysed with respect to wind direction which can be done by the available 20-min averaged wind direction.

Land use is also of great influence.According to the crops which are established,the wind field structure can vary.From one year to another,and also within a year it will vary.For grass it does not considerably change, but for maize it varies very fast during its growing season.
Figure 5.3.shows the land use within a radius of 250m for 1983 and 1984.Some differences can be seen,especially the location of crop maize to the North and East of the stations.Fixed obstacles as the farm's buildings are also important,since they disturb the wind field with the western winds.

The comparison of the results of actual evapotranspiration are made on 20-min,hourly,daily and daylight values.It is a comparison of values obtained by different methods or for different gradients.

5.2.2.2.Results obtained by the energy balance method:comparison of the results for different temperature gradients:

The analysis of the hourly values,of daylight or daily values gives identical results.The correlation is always good and the relationship is linear.In table 5.6.,the coefficients of the best straight line and the coefficients of correlation are recorded for the relations EH1-EH2 and EH2-EH3.

In 1983,August has a minor good result than the other months.The fact that it was a dry month may be an explanation.The results in 1984 are worse,especially June and July.In 1984,more problems had to be faced concerning the instrumentation,and more particularly the net-radiometer.

The correlation of EH1 or EH2 with EH3 is generally better than EH1-EH2,that is explainable since EH3 is intermediate to EH1 and EH2. This can also be seen in figure 5.4. a and b.

It can be concluded that the heat transfer is nearly constant in the surface layer,which is apparently in contrast with the momentum turbulent transport (u*).

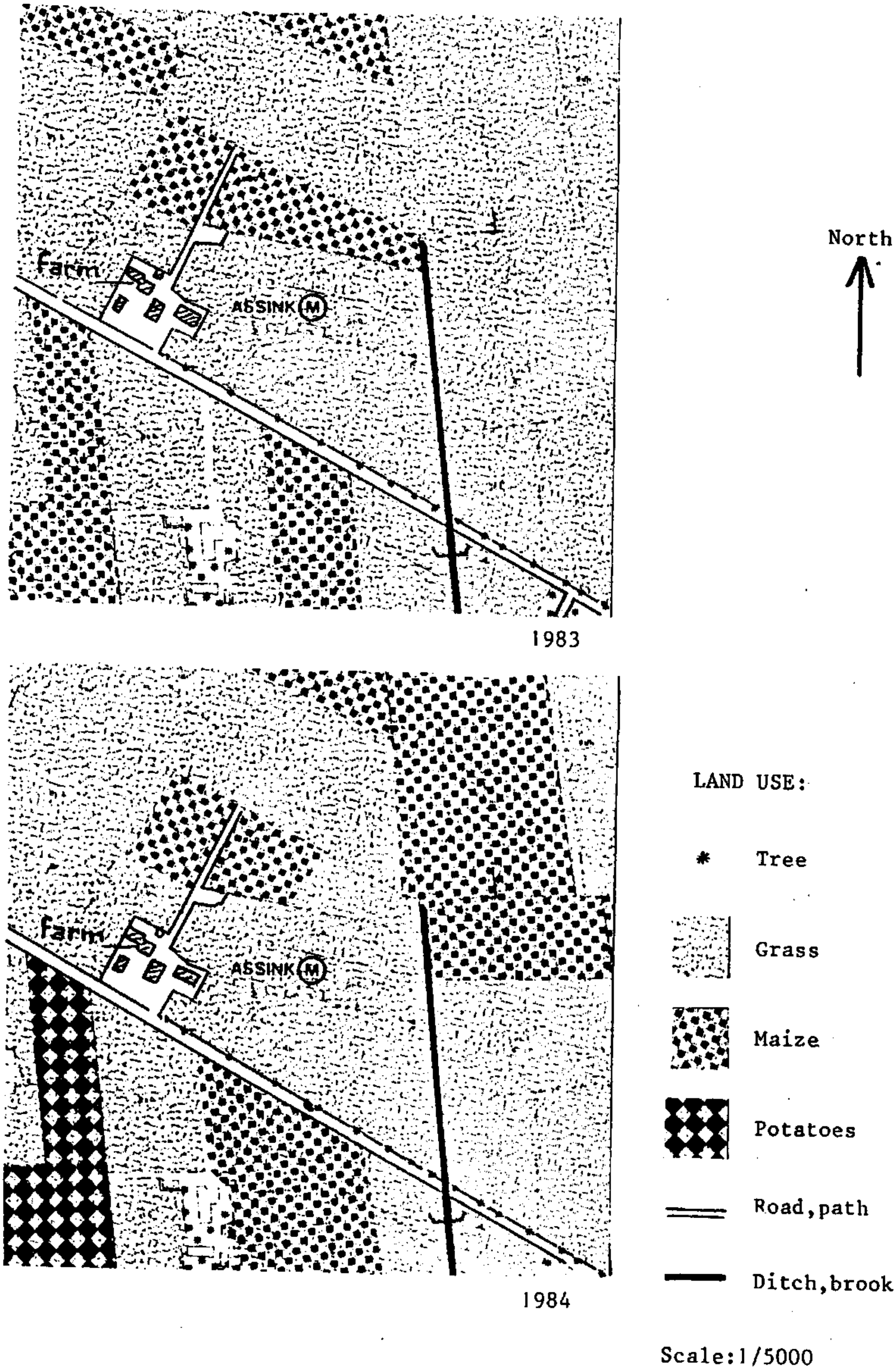


FIGURE 5.3: Maps of land use within a radius of 250m around the meteorological station, for the growing seasons 1983 and 1984.

TABLE 5.6:Comparison of the latent heat flux at different levels
--------- obtained by the indirect method(hourly values)

	EH2 = a.EH1 + b:				EH3 = a.EH2 + b:		
	a	b	r	N	a	b	r
May 1983	0.98	1.92	0.994	243	1.00	-0.81	0.998
Jun.1983	1.01	1.20	0.995	548	0.99	0.63	0.998
Jul.1983	1.00	0.83	0.982	692	0.98	1.32	0.991
Aug.1983	0.96	0.94	0.922	658	0.92	4.72	0.959
Sep.1983	1.01	2.33	0.988	708	0.97	-0.40	0.995
Oct.1983	0.99	5.26	0.985	660	0.98	-1.98	0.996
May to Oct.1983	0.99	1.95	0.978	3509	0.98	0.58	0.989
Jun.1984	1.12	1.30	0.987	436	0.92	0.27	0.994
Jul.1984	1.12	-0.27	0.993	111	0.94	0.53	0.998
Sep.1984	1.00	2.28	0.971	271	0.97	-0.12	0.971
Oct.1984	1.01	2.37	0.999	49	0.99	-1.37	1.000
Jun. to Oct.1984	1.09	2.29	0.986	867	0.93	-0.24	0.994

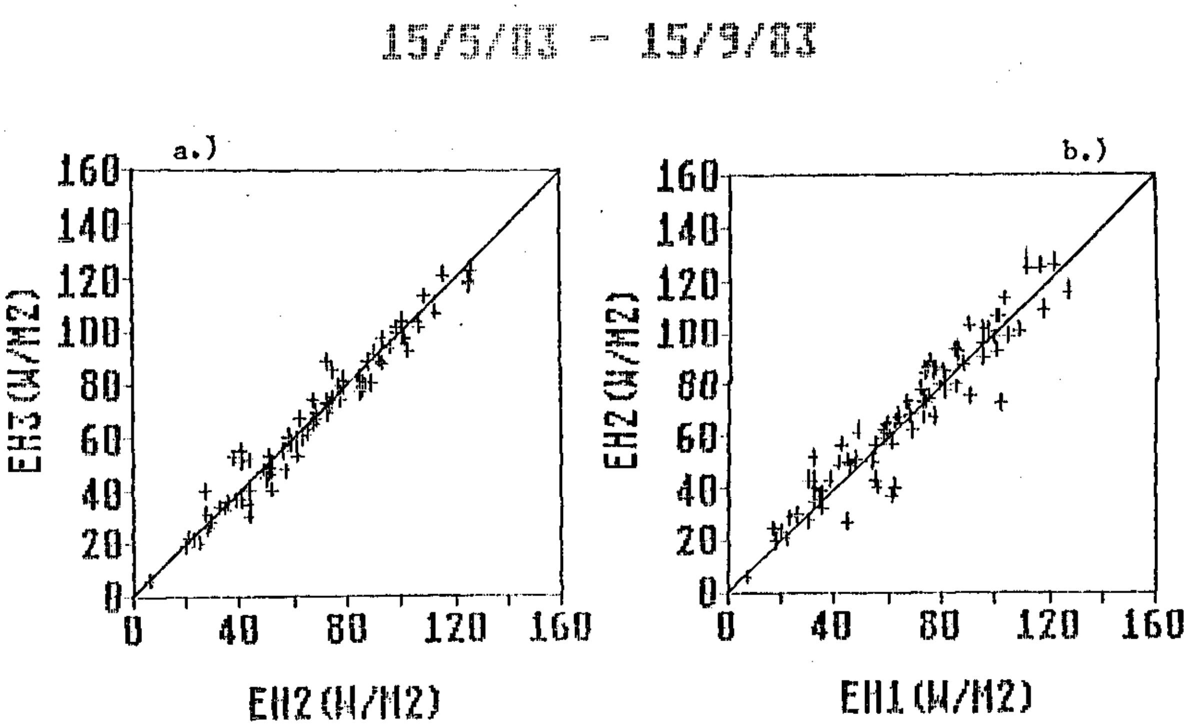


FIGURE 5.4.:Comparison between the values of the latent heat flux for
----------- two different temperature gradients,for mean daily values.

The difference between the results for two different gradients is not the same for the three methods. The direct method produces more scattered results than the Bowen ratio and indirect methods, as shows us figure 5.5.

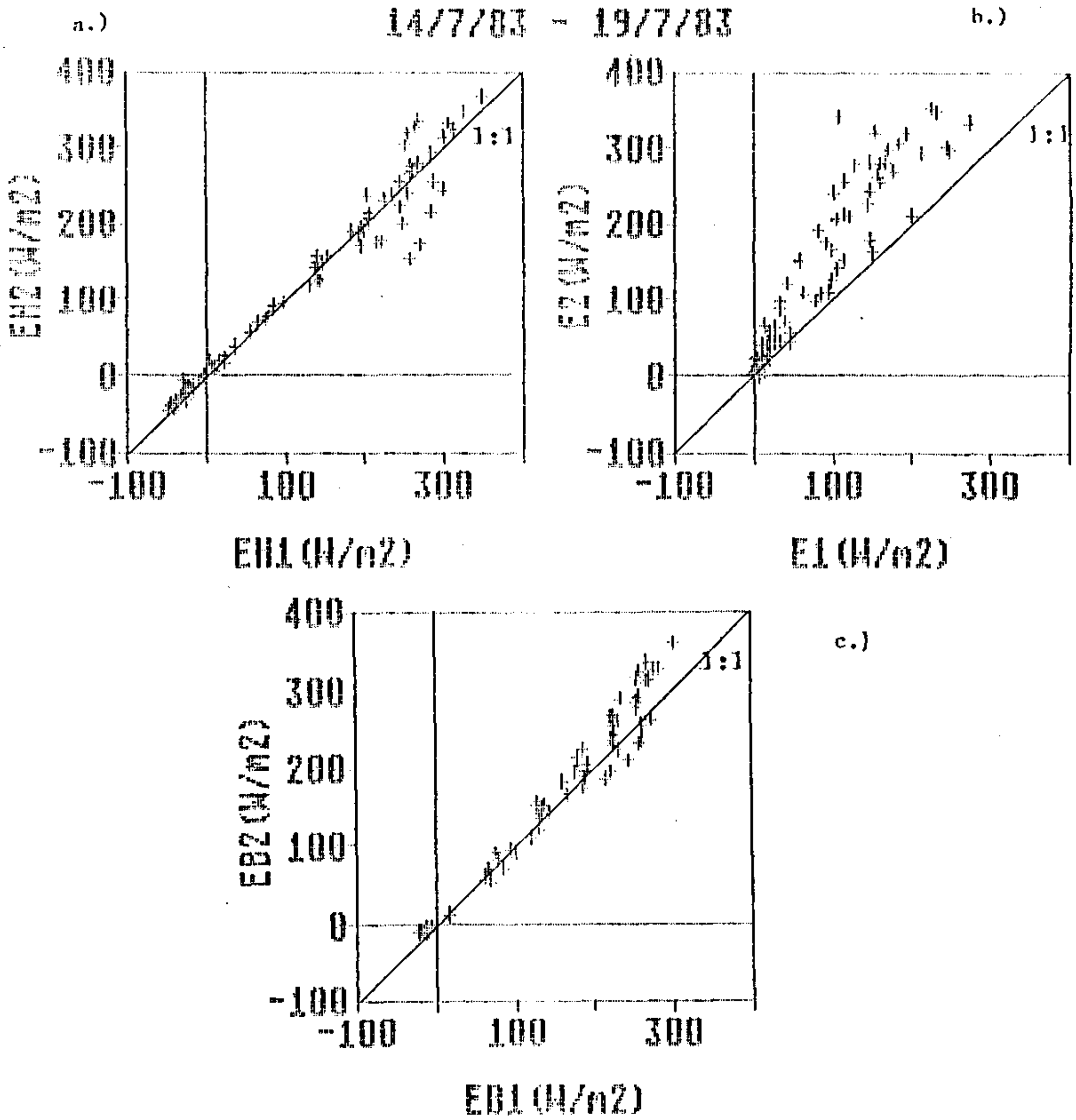


FIGURE 5.5.:Differences between the results obtained for different
----------- gradients for the indirect method (a), direct method (b) and Bowen ratio method (c), for mean daily values.

5.2.2.3.The direct and indirect methods:

The statistical analysis of the hourly data shows that although the correlation is rather good (r is varying over a range from 0.809 to 0.930 for hourly values), the ratio between EH and E is much too small. Except a few cases concerning the upper level, EH is always larger than E. The results are presented in table 5.7., and in figure 5.6.

TABLE 5.7: Comparison of the latent heat flux calculated by the indirect method and by the direct method (Hourly values, W/m2)

		a	b	r	N
E1 = a.EH1 + b, Level 1.30m-3.15m	Jun.1983	0.56	14.16	0.877	166
	Jul.1983	0.52	9.50	0.921	165
	June and July 1983	0.54	11.99	0.896	331
	Aug 1984	0.25	19.83	0.828	49
	Sep.1984	0.26	7.51	0.869	92
	Aug. and Sep.1984	0.25	11.89	0.826	141
E2 = a.EH2 + b, Level 3.15m-7.14m	Jun.1983	0.51	19.05	0.933	166
	Jul.1983	0.81	20.10	0.895	165
	June and July 1983	0.67	19.68	0.877	331
	Aug 1984	0.28	26.36	0.839	49
	Sep.1984	0.81	34.41	0.899	92
	Aug. and Sep. 1984	0.58	34.52	0.814	141
E3 = a.EH3 + b, Level 1.30m-7.14m	Jun.1983	0.45	8.25	0.918	166
	Jul.1983	0.58	6.19	0.930	165
	June and July 1983	0.52	7.26	0.918	331
	Aug 1984	0.27	16.44	0.809	49
	Sep.1984	0.53	12.13	0.911	92
	Aug. and Sep. 1984	0.42	15.10	0.852	141

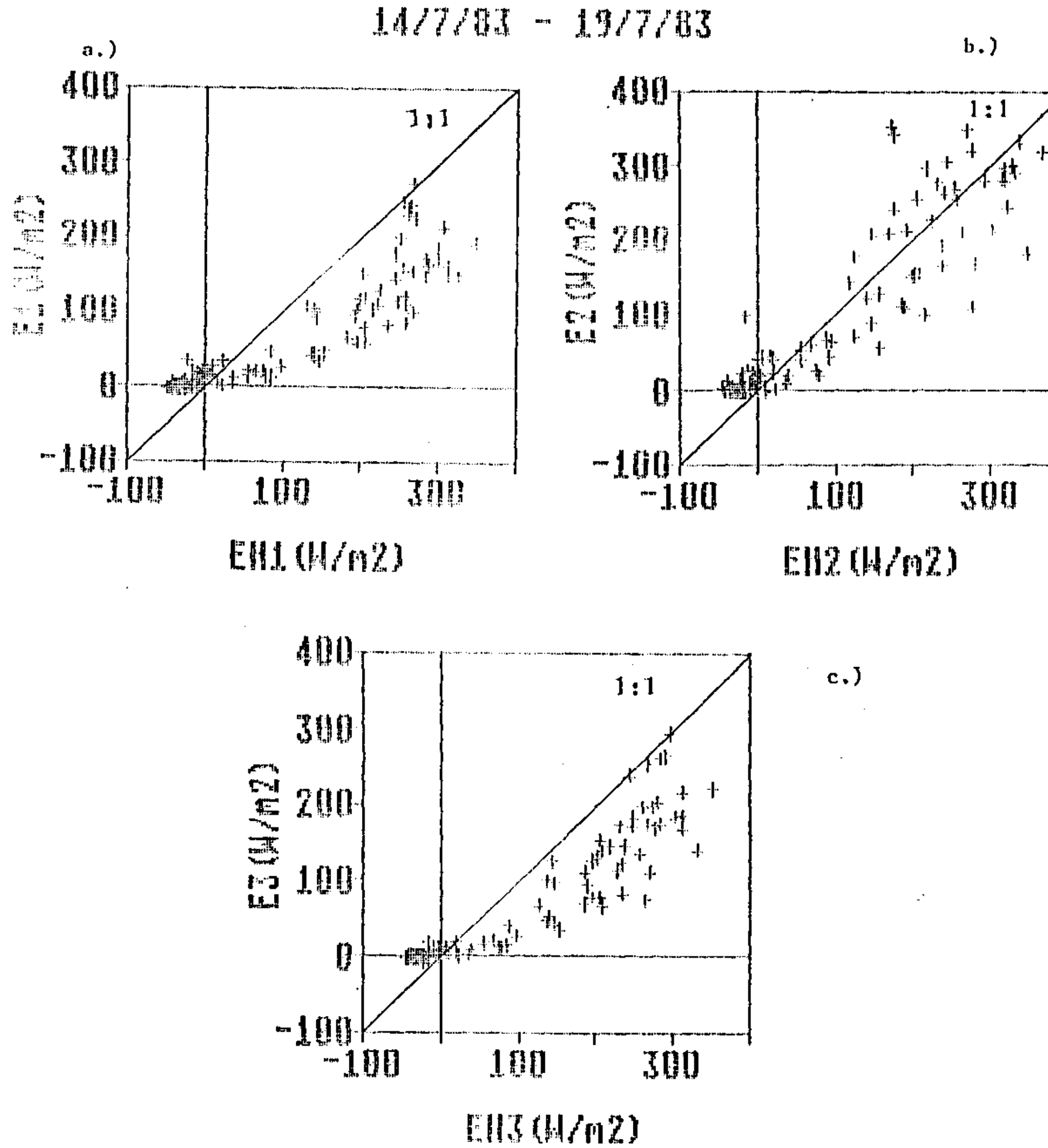


FIGURE 5.6.: Comparison between the values of actual evapotranspiration obtained from the indirect method and these obtained from the direct method.

The sensitivity analysis may give an explanation:as an example,an error of +0.03 K in Td does E increase with 22 to 43% and does EH increase with 2 to 7% depending on measurement level.If such an error is accompanied by a small positive error on Tw,EH will still increase ,and the shift between the two values will be very important.
The fact that the difference in EH minus E is always positive show a systematic error made by one or more of the sensors.

The statistical analysis has also been made on daylight and daily values of actual evapotranspiration calculated by both methods but the size of the sample is too small to show significant results.

Table 5.8. shows the available daily values calculated by these two methods.Two points are important :(i)The direct method generally underestimates the evapotranspiration,except for the upper level in July 1983.(ii)The direct method gives results for the three differences which are more scattered,as figure 5.5.b has shown.

TABLE 5.8:Comparison of the latent heat flux calculated by the indirect and direct methods:daily values,W/m2

	E 1	E 2	E 3	EH 1	EH 2	EH3
24/6/1983	55.6	54.0	44.2	80.3	85.5	82.7
25/6/1983	63.6	68.8	53.5	67.1	73.2	69.3
26/6/1983	74.6	71.8	57.7	94.9	101.7	97.9
27/6/1983	48.0	57.2	34.6	67.6	68.4	67.6
28/6/1983	44.9	41.6	27.4	72.1	78.0	74.6
29/6/1983	18.1	40.4	16.5	17.9	20.0	18.9
14/7/1983	44.2	62.0	43.4	68.6	62.5	67.4
15/7/1983	47.3	79.6	48.9	99.9	106.8	102.3
16/7/1983	58.6	92.9	59.3	90.7	75.2	85.5
17/7/1983	75.1	118.7	80.3	85.1	92.8	89.2
18/7/1983	48.9	97.9	54.0	96.3	101.2	97.8
2/9/1984	23.1	81.4	50.5	44.9	49.8	45.9

In 1984,wet-bulb measurements were done for twenty days,but net radiation was not completely measured and there is often no result for EH and the comparison is only possible for one day.

5.2.2.4.:The Bowen ratio and the indirect methods:

Table 5.9. shows the results of the analysis of the relationships between the hourly values of the evapotranspiration calculated with the Bowen ratio and the energy balance methods.The correlation coefficients are higher than 0.956 so that it can be said that the correlation is strong.The regression line is always shifted from the 1:1 line in the way EB<EH,as it is shown in figure 5.7

TABLE 5.9:Comparison of the latent heat flux calculated by the indirect and Bowen ratio methods:hourly values,W/m2

		a	b	r	N
EB1 = a.EH1 + b	Jun.1983	0.89	5.01	0.993	115
	Jul.1983	0.87	8.57	0.995	109
	June and July 1983	0.88	6.54	0.994	224
Level 1.30m-3.15m	Aug 1984	0.64	19.63	0.956	33
	Sep.1984	0.60	8.25	0.988	63
	Aug. and Sep. 1984	0.61	11.89	0.967	96
EB2 = a.EH2 + b	Jun.1983	0.95	-1.61	0.996	118
	Jul.1983	0.99	1.47	0.992	124
	June and July 1983	0.97	-0.12	0.993	242
Level 3.15m-7.14m	Aug 1984	0.60	26.32	0.981	31
	Sep.1984	0.86	16.00	0.974	55
	Aug. and Sep. 1984	0.73	23.59	0.963	86
EB3 = a.EH3 + b	Jun.1983	0.93	-0.01	0.994	118
	Jul.1983	0.93	3.16	0.996	117
	June and July 1983	0.97	1.56	0.995	235
Level 1.30m-7.14m	Aug 1984	0.61	26.93	0.983	29
	Sep.1984	0.76	16.96	0.989	49
	Aug. and Sep.1984	0.68	22.81	0.981	78

For the available hourly values,the average has been calculated in June and July 1983 and the results are the following:

June 1983 : EH1=98.3 EB1=92.8
EH2=103.5 EB2=96.7
EH3=99.4 EB3=92.2

July 1983 : EH1=131.6 EB1=122.9
EH2=117.5 EB2=117.4
EH3=123.8 EB3=118.9

Except for the upper gradient in July ,the Bowen ratio method gives a systematically lower (about 6%) result than the energy balance method.An error in temperature measurement may also explain this difference.

The results of 1984 are much more scattered,which is due to the more numerous problems encountered with the intrumentation.

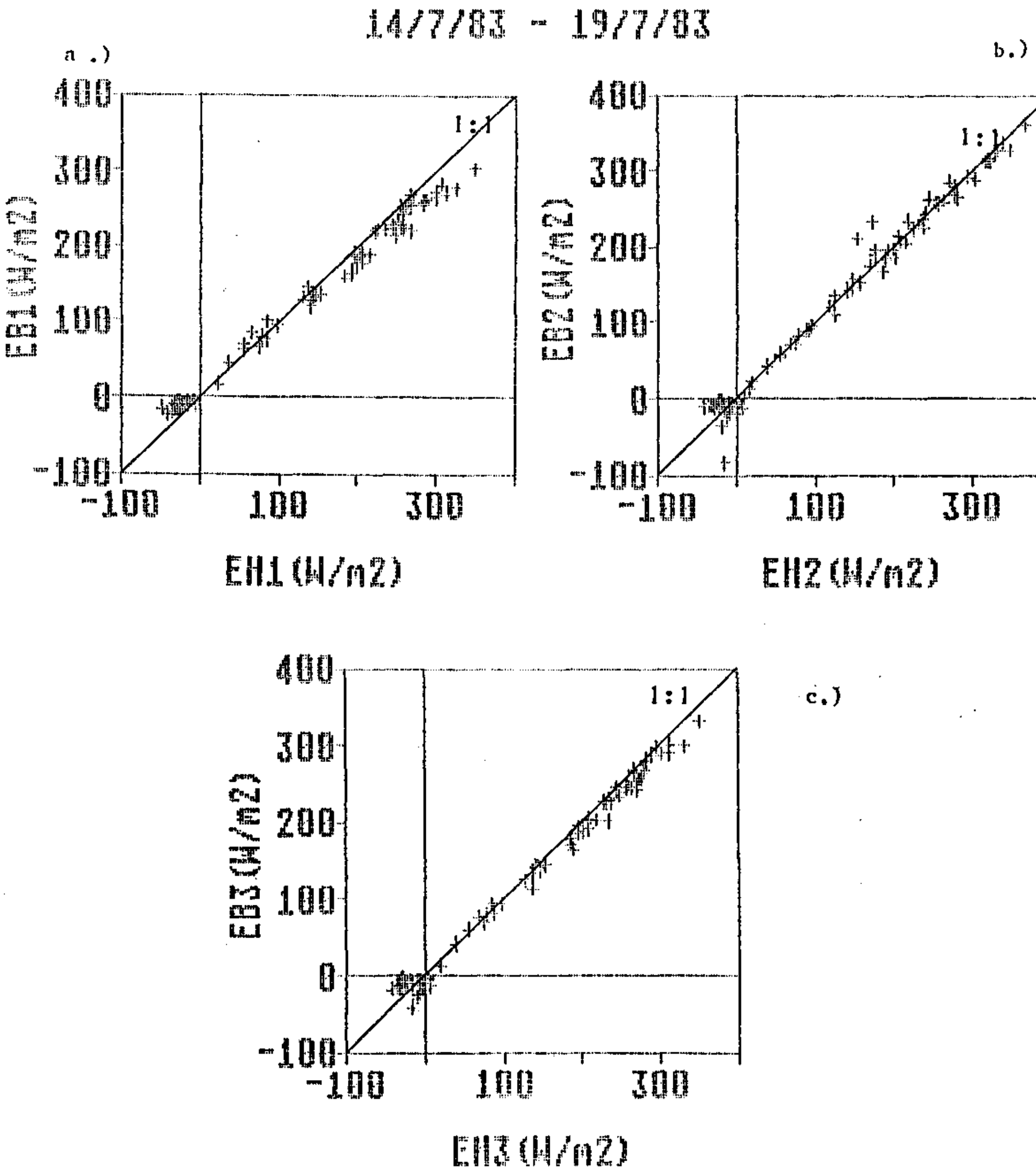


FIGURE 5.7.:Comparison between the values of actual evapotranspiration calculated with the indirect method and these calculated with the Bowen ratio method,hourly values.

5.2.3.Potential evapotranspiration:

5.2.3.1.Comparison between two different methods:

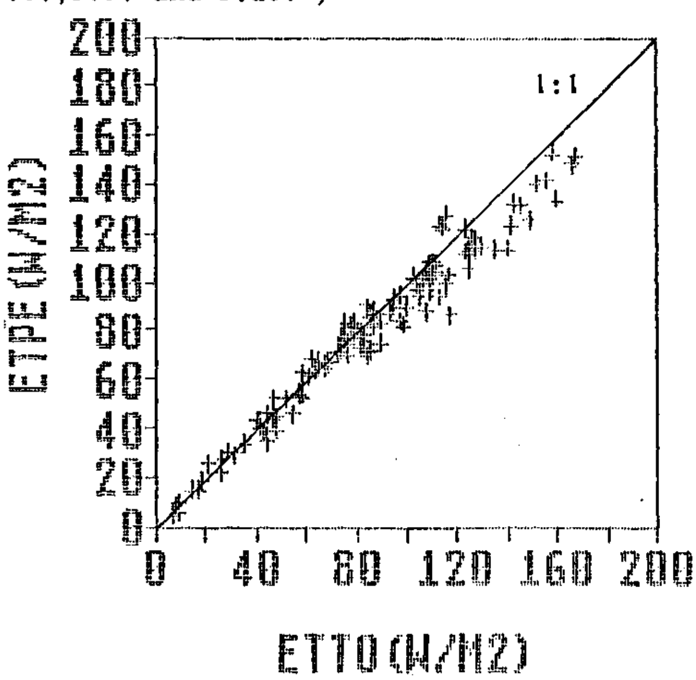
The results obtained for each method have been compared to the results obtained by the formula of Thom and Oliver.The regression line and the coefficient of correlation were calculated for all available values for the whole period (1st of January 1983-31st of October 1984) for the formulas of Penman and of Makkink.For the formulation of Priestley and Taylor,the average was calculated and compared with Thom and Oliver for three periods:from April to September of each year,from May to August of each year and for the same period as the latter excluding the dry months of July and August 1983.

Table 5.10 shows the results for the whole period(422 data):

TABLE 5.10.:Comparison of the results of potential evapotranspiration
----------- obtained by different methods:

Formulas	a	b	r
ETPE = a.ETTO + b	0.96	-2.6	0.99
ETM1 = a.ETTO + b	0.89	3.4	0.962
ETM2 = a.ETTO + b	0.77	6.3	0.951

Some graphs show the relations between these methods for the period going from the 15th of May to the 15th of September 1983.(See figures 5.8.,5.9. and 5.10.)



15/5/83 - 15/9/83

FIGURE 5.8.:Potential evapotranspiration:comparison of the results
----------- obtained by the formulas of Penman and by Thom and Oliver.

The mean values over the different periods are presended in table 5.11.

TABLE 5.11.:Mean values of potential evapotranspiration over different periods:

Period	Formula	Mean value (W/m2)
1/1/83-31/10/84	ETTO ETPE ETM1 ETM2	40.3 36.2 39.2 37.3
1/4/83-31/9/83 + 1/4/84-31/9/84	ETTO ETPT	53.2 37.2
1/5/83-31/8/83 + 1/5/84-31/8/83	ETTO ETPT	54.9 39.0
1/5/83-30/6/83 + 1/5/84-31/8/84	ETTO ETPT	38.1 23.7

What can be seen from this is:

-(i) the best correlation is between the formula of Penman and of Thom and Oliver,and the worse is between the formulas of Thom and Oliver and of Makkink(2).

-(ii)Over a long period,the formulations of Thom and Oliver and of Makkink(1) give average results which are very close (underestimation of 2.7% for ETM1 compared to ETTO).

-(iii)The difference between the results of Penman and of Thom and Oliver is at the most of 10% (ETPE<ETTO).This underestimation was already pointed out by Thom and Oliver when they developped their formula.

-(iv)Priestley and Taylor's formula gives an average which is 30% less than the value resulting from the formula by Thom and oliver,even if the calculation is done over a period which seems to be more adapted to the use of the formula.

5.2.3.2.Potential and actual evpotranspiration:

Potential evapotranspiration is the amount of water which can be evaporated if the availability of water is not a limiting factor.In the Netherlands,this condition is very often satisfied.That means that the actual evapotranspiration may be estimated by the potential evapotranspiration during a large period of the year and not seldom during the whole year.

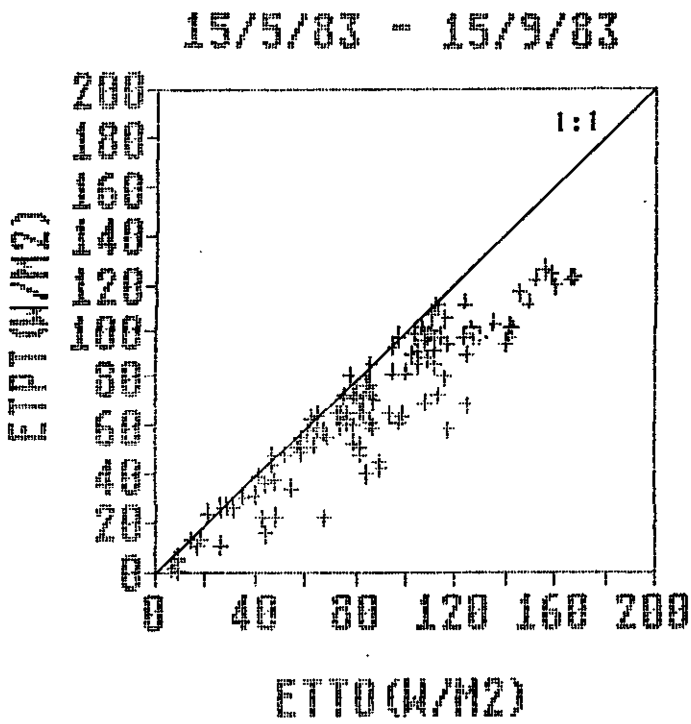


Figure 5.9.:Potential evapotranspiration:comparison between the
------------ results obtained by the formulas of Thom and Oliver and of Priestley and Taylor.

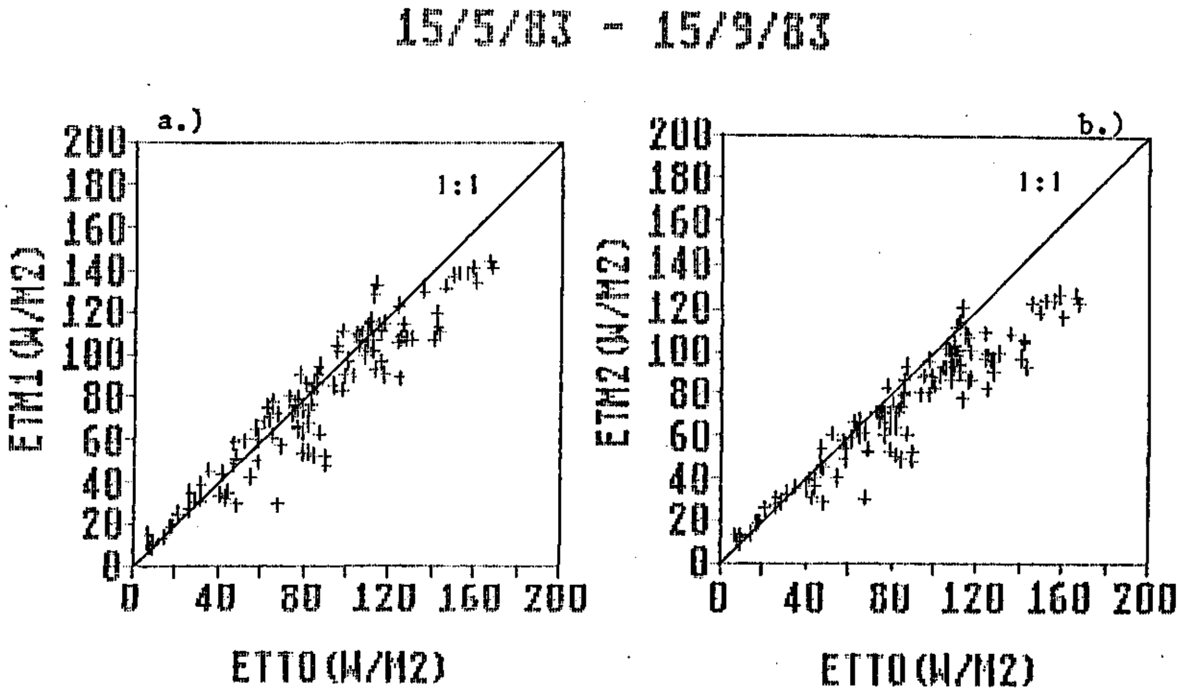


FIGURE 5.10.:Potential evapotranspiration:Comparison between the
------------ results obtained by the formulas of Thom and Oliver and of Makkink (standard formulation (a),and formulation including G (b))

As an example, figure 5.11.a-d represents the daily values of the potential evapotranspiration calculated by different equations and the actual evapotranspiration calculated by the energy balance method for a period.

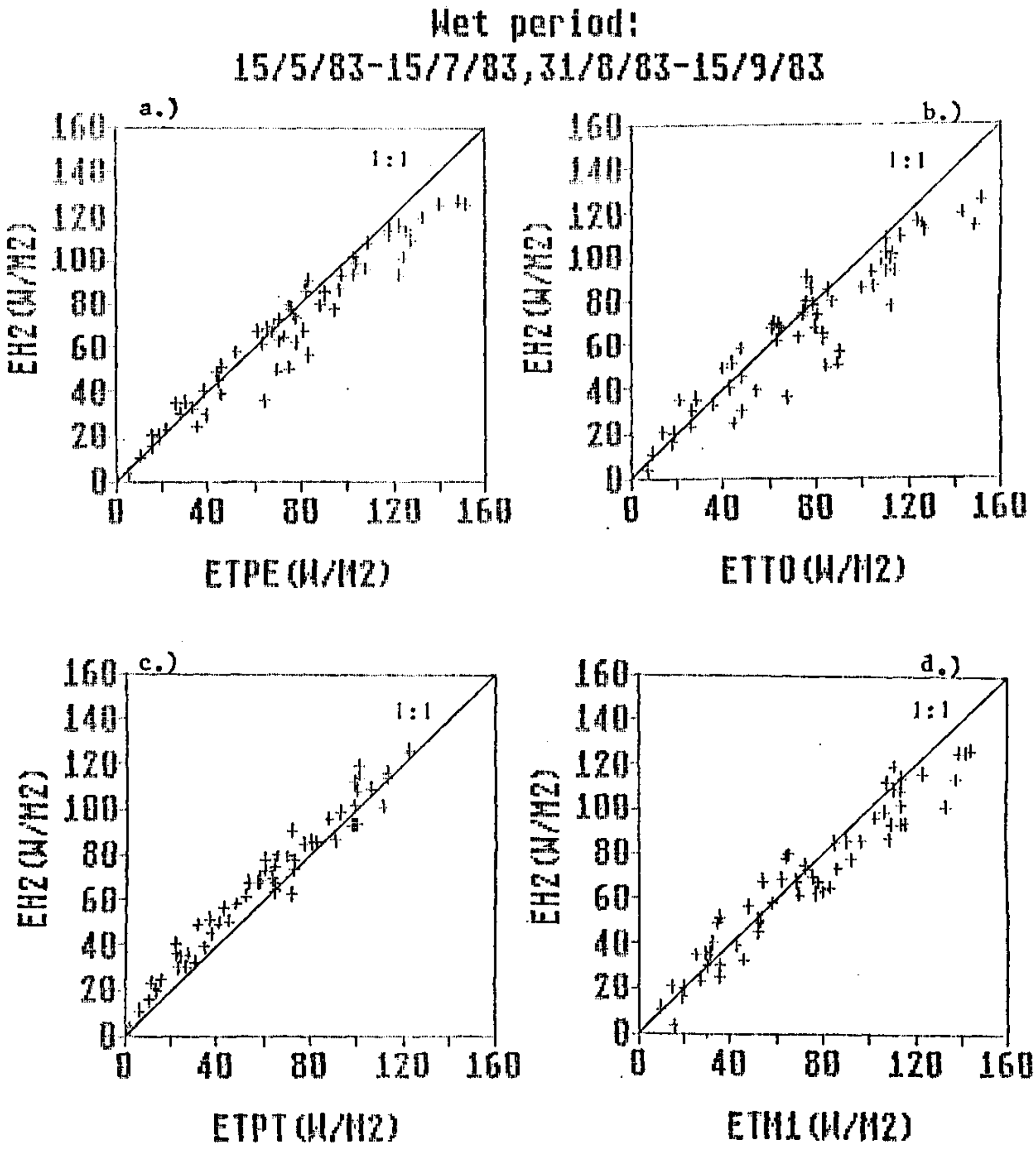


FIGURE 5.11.: Comparison between actual and potential evapotranspiration, for various equations of the potential evapotranspiration (Penman (a), Thom and Oliver (b), Priestley and Taylor (c) and Makkink (d)) for a well watered period.

In figure 5.12.,the same comparison is made for a dry period going from the 15th of July to the 30th of August 1983.

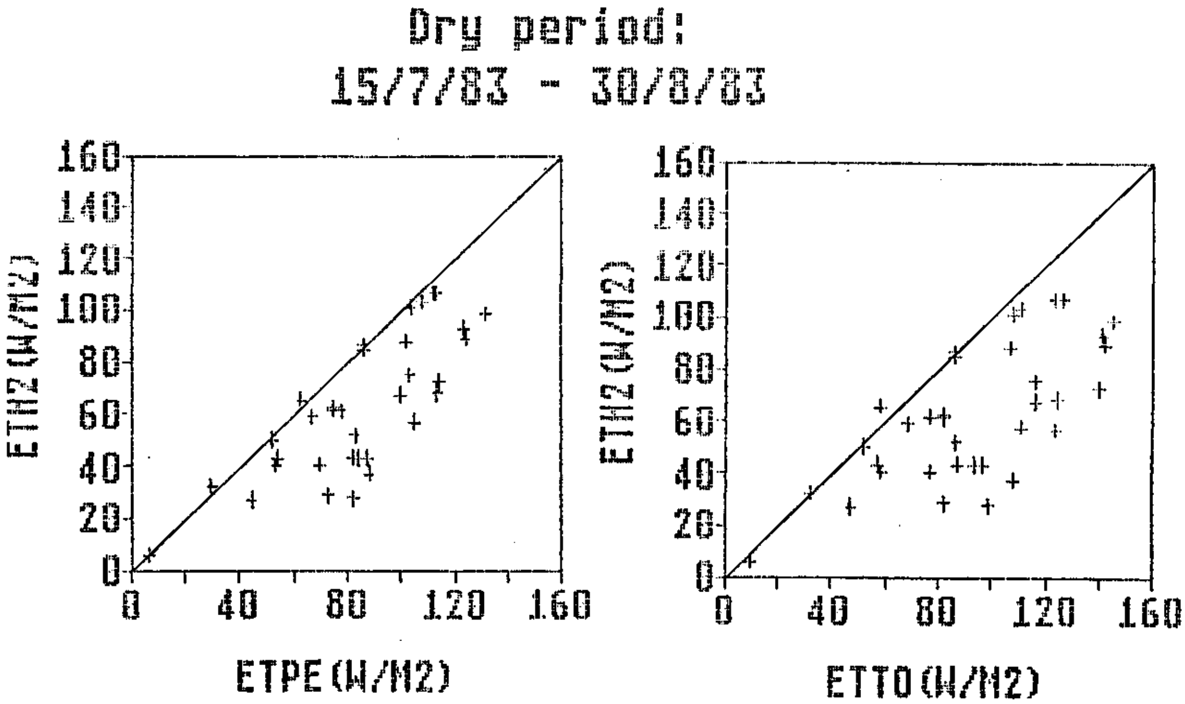


FIGURE 5.12.:Comparison between actual and potential evapotranspiration from Thom and Oliver(a) and Penman (b),for a dry period.

Although the agreement is good for a period when the availability of water is not a limiting factor,the agreement is not acceptable for a dry period.

5.2.4.The advection-aridity method:

The advection-aridity method was developed to calculate the actual evapotranspiration from the meteorological data usually used in the calculation of potential evapotranspiration,especially when the latter is not a good approximation of the first one,because it is too dry.

A dry period had been selected in 1983:from the 15th of July to the 30th of August.Rainfall amount was only 38.5 and the number of rainy days was 11.The period followed at a period of ten days without rain,it can thus be concluded that the required amount of water for the vegetation is not available.

Figure 5.12. already showed that the potential evapotranspiration ,as expressed by Thom and Oliver or by Penman,is not a good estimation of actual evapotranspiration.

-(i)For nearly every day:ETPE is larger than EH2.
-(ii)The correlation coefficient r is 0.77.
-(iii)The best straight line ,EH2=0.72.ETPE + 0.8,is far from the bisector.

Three formulations to test the advection-aridity approach (4.36),(4.37)and (4.38) are used for this dry period.The results are explained and discussed here after.For daily values,data calculated with the first combination (4.36) are in the best agreement with data of actual evapotranspiration calculated from the energy budget method:the correlation coefficient is 0.86 and the best straight line is ETA1 = 0.78.EH2 + 7 and it is very near to 1:1,(see figure(5.13.)).Results from the third combination (4.38) leads also to rather good results (r=0.83 and the best straight line is ETA3 = 0.78.EH2 + 1, see figure 5.14.) but underestimates the evapotranspiration.The mean values for this period are:62.4 W/m2 for EH2,58.2 W/m2 for ETA1,50.1 W/m2 for ETA3.Figures 5.13. and 5.14. show that the points which are the farthest from the 1:1 line are for low values of evaporation,which confirms that the approach may be useful in the first place for summer periods.These two formulations represent an improvement as compared to the estimation by the potential evapotranspiration.But results computed with the second combination (4.37) are very scattered (r=0.62) and too high.This can be seen from the graph representing ETA2 versus EH2 (figure 5.15.) and also from the average over the considered period:ETA2=85.0 W/m2.

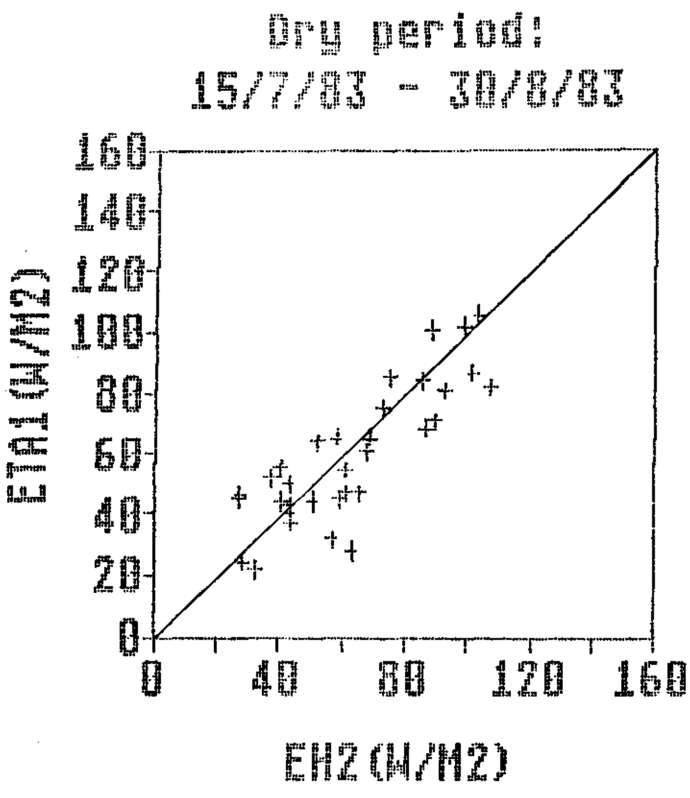


FIGURE 5.13.:Actual evapotranspiration calculated by the energy
------------- balance equation and by the advection-aridity(First combination,equation 4.36.)

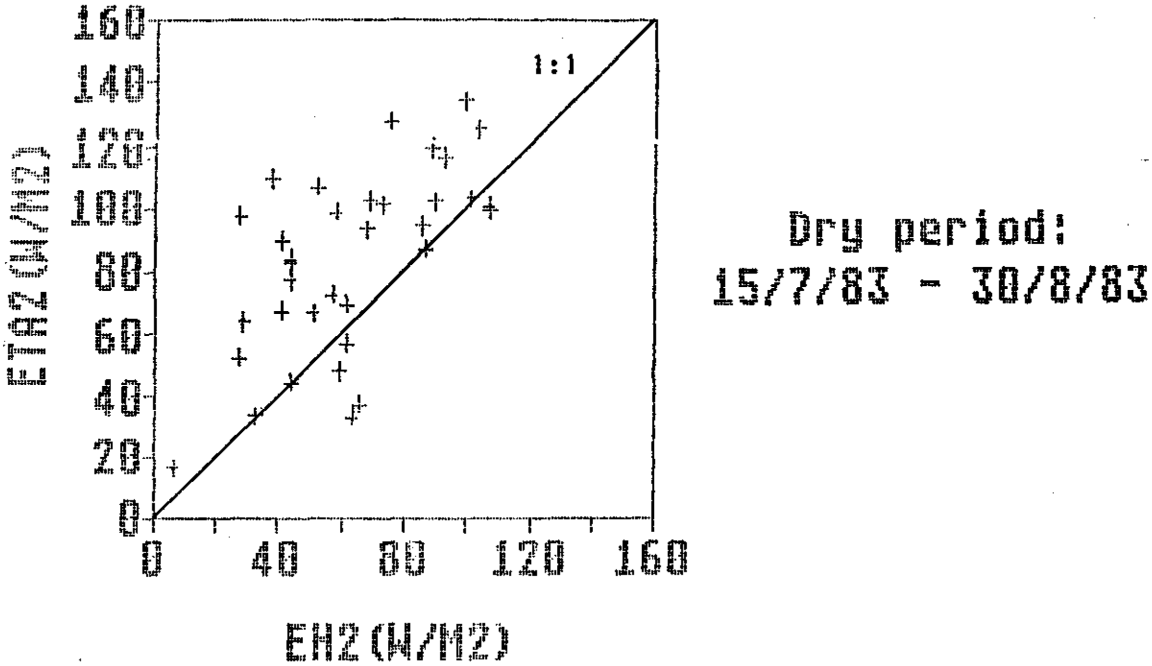


FIGURE 5.14.:Actual evapotranspiration calculated by the energy
------------- balance equation and by the advection-aridity method
(third combination equation 4.38)

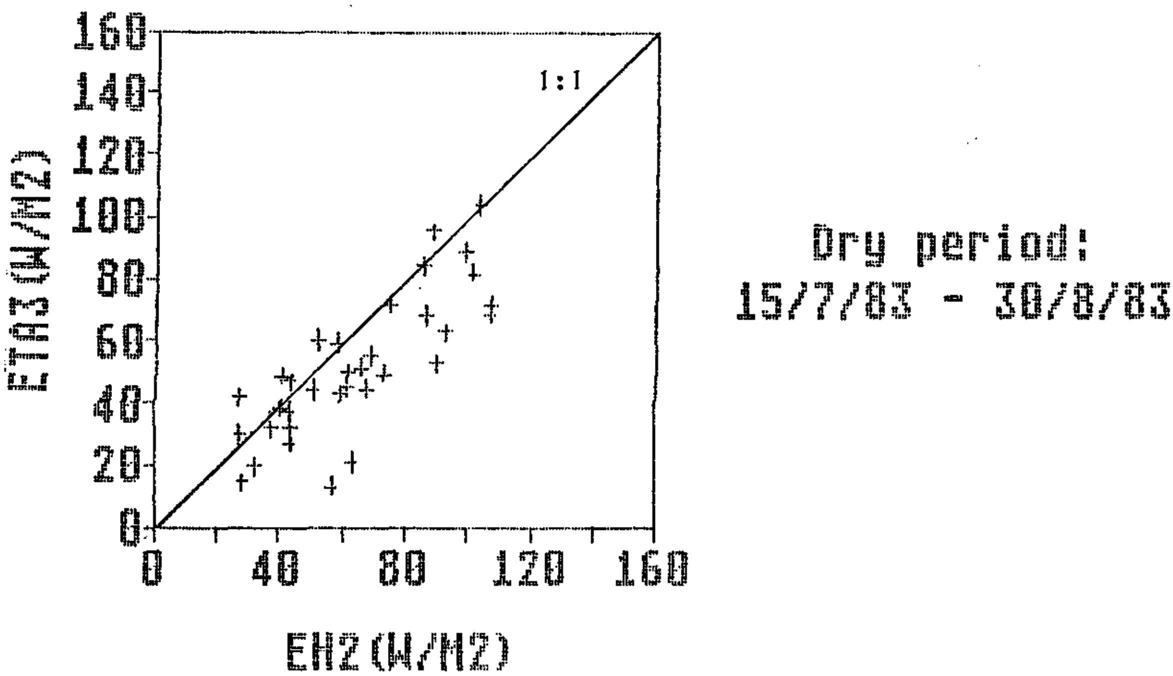


FIGURE 5.15.:Actual evapotranspiration calculated by the energy
------------- balance equation and by the advection-aridity method
(second method, equation 4.37.)

Over this period, the mean values of EH2, ETA1, ETA2 and ETA3 were calculated over three consecutive days and the results are less scattered as figure (5.16.) shows it.
Results from the third combination are very well correlated with EH2 ($r=0.96$) but underestimated. With the first relation, the correlation is worst ($r=0.84$) but the linear relationship seems to give the best approach.

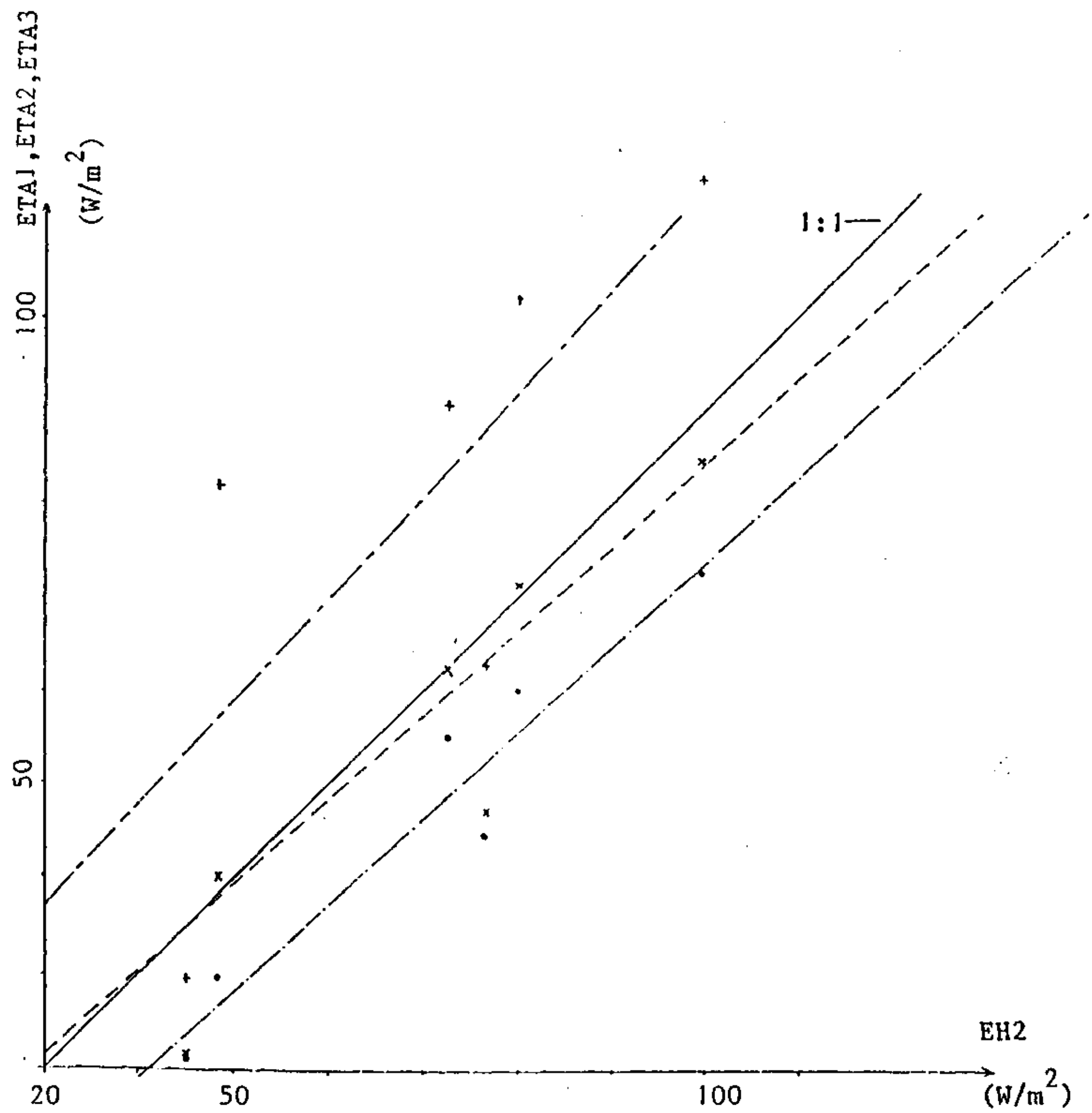


FIGURE 5.16.: Mean daily values on three consecutive days, during the period going from the 15th on July to 30th of August 1983:
Comparison of the data obtained from the advection-aridity method and from the indirect method for the actual evapotranspiration.

- - - - - : best straight line: $ETA1=0.90\ EH2 + 3.4$; $r=0.83$ (×)
——-——: " : $ETA2=1.10\ EH2 + 15.0$; $r=0.76$ (+)
——·——: " : $ETA3=0.92\ EH2 ++8.8$; $r=0.96$ (•)

CHAPTER 6:THE WATER BALANCE:

6.1.Introduction:

As it has been pointed out in chapter 3,the water balance enables a verification of the values of the evapotranspiration.It is all the more useful as no direct measurement of the evapotranspiration is done because they are not reliable.

The equation of the water balance is in absence of seepage or deep percolation:

$$\sum_{D1}^{D2} (P - D - E) = \Delta S \qquad (6.1)$$

where D1 and D2 represents the two dates between which the balance is made.
P is the precipitation (mm/day)
D is the discharge (mm/day)
E is the evapotranspiration (mm/day)
ΔS is the difference in soil moisture content of the soil between D1 and D2.

The biweekly data of soil moisture content measured in Hupselse Beek catchment by a neutron probe are still not available.The calculations can be done using the groundwater levels,measured every two weeks.

The balance has to be made between two dates satisfying two conditions:
-a few days after rainfall
-not during a dry period
In this way,the soil moisture profile is in a state of equilibrium.The two dates which had been chosen are the 28th of December 1982 and the 15th of October 1984.

6.2.Calculation of the difference in soil moisture content from the groundwater levels:

The water retention curve (or pF curve) represent the volume percentage of moisture content as a function of the suction h.The suction is expressed in cm water column and represents the negative pressure needed in a point to withdraw soil moisture at this point.
By definition,pF = log10 |h|.

In Hupselse Beek catchment,two mean curves are known from the research on soil variability (Hopmans and Stricker,1987).One curve was derived from A-horizon data and one from B-horizon data.The A-horizon is the upper part of the soil,the rootzone,concerning here the first 30 cm of the soil.The B-horizon is the lower part of the soil profile.

The two mean curves are described by the Van Genuchten-Mualem model:

$$\theta = \left[\frac{1}{1 + |\alpha h|^{n}}\right]^{m} \qquad (6.2)$$

$$\theta(h) = \theta_s \times \theta \qquad (6.3)$$

where θ is the saturation degree (-)

θ_s is the saturation value of the soil moisture content (cm3/cm3)

$\theta(h)$ is the soil moisture content for the suction h

The numerical data are:

-for A-horizon: $s = 0.4024 (cm^3/cm^3)$
$\alpha = 0.01924$
$n = 1.5931$
$m = 1\text{-}1/n = 0.3723$

-for B-horizon: $s = 0.3195 (cm^3/cm^3)$
$\alpha = 0.02043$
$n = 1.8187$
$m = 0.4502$

In Hupselse Beek watershed, the groundwater table is measured at 35 sites. For each date, the mean value, as a representative value for the whole catchment, is calculated over the points where the measurement was effectively done at both dates.
The groundwater table was at 84cm on the 28th of December1982 and at 87cm on the 15th of October 1984.

The retention curve is then plotted for these two levels in figure 6.1.

The area included between these two curves corresponds to the variation in the soil moisture storage for the mean profile. The surface between the two curves is calculated by a step by step integration from 0 to the deeper level (87cm here). In this case, the storage of water in the soil differs by -4.3mm between the 28th of December 1983 and the 15th of October 1984. (It became somewhat dryer).

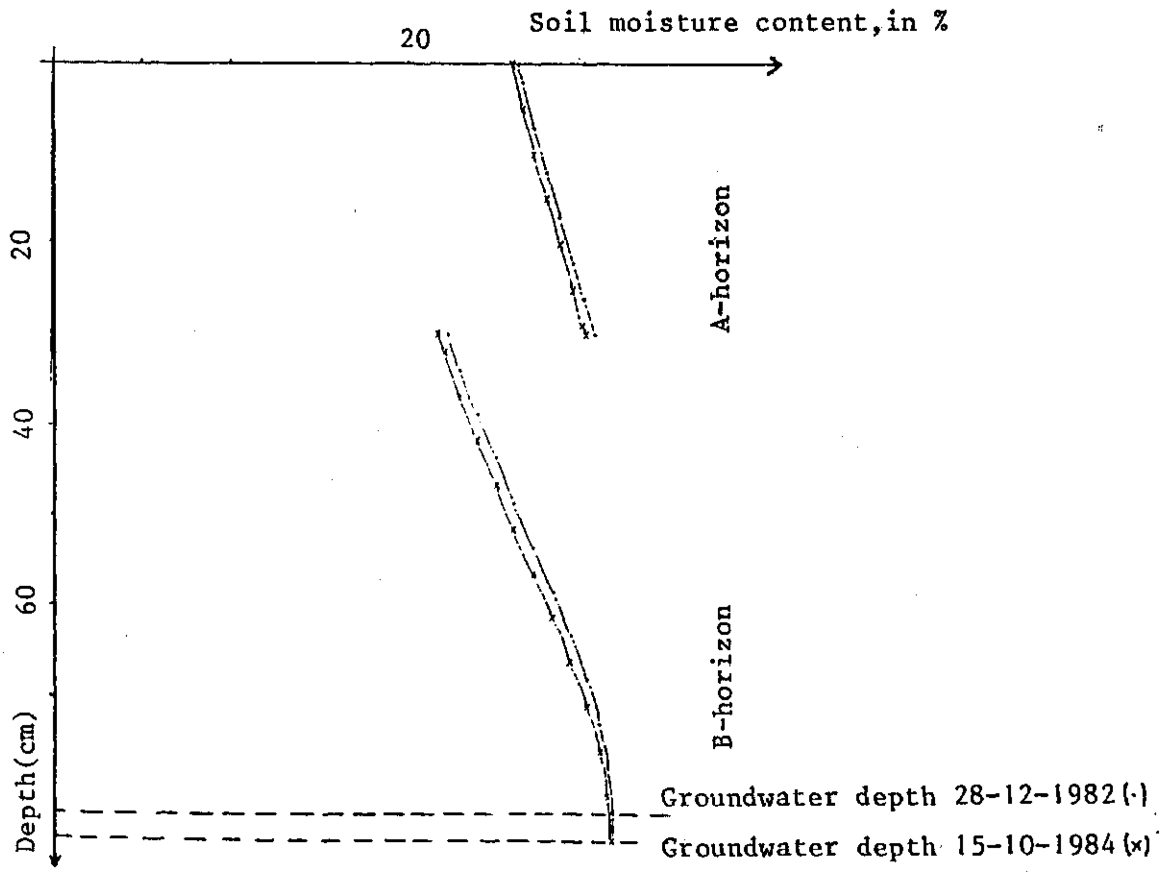


FIGURE 6.1.:pF curves for the two considered groundwater tables

6.3.Water balance calculations:results:

The left hand side of equation (6.1.) has to be calculated and then compared to the value which has been found for the right hand side.

As input data,the daily values of evapotranspiration,rainfall and discharge have been taken.

Data of different combinations of methods have been taken for the evapotranspiration according to the period:

-during the growing seasons:from the 15th of April to the 15th of September in 1983 and 1984:

values of actual evapotranspiration,calculated either by the values from the indirect method(EH1 or EH2 or EH3) or by the advection-aridity method (ETA1 or ETA2 or ETA3).These latter values were only used for a water restricted period from the 15th of July to the 31st of August 1983.

-outside the growing season:from the 28th of December 1982 to the 14th of April 1983,from the 16th of September 1983 to the 14th of April 1984 and from the 16th of September to the 15th of October 1984,or during the growing season if a value of actual evapotranspiration is missing:

values of the potential evapotranspiration calculated by the formulations of Penman,or of Thom and Oliver or Makkink.

Daily rainfall is normally calculated by from the 20-min data.If some values are missing,daily values,also measured in Hupsel,are used.

The discharge measurement is done at the outlet of the watershed with an H-flume.

All the components of the water balance have to be expressed in mm/day.So the values of the evapotranspiration in W/m2 have to be multiplied by $3.5.10^{-2}$ and the values of the discharge in m3/s by 13.3 to be converted in mm/day.The explanation of these conversion factors is given at the page 'symbols and notations'.

Results are shown in table 6.1.

TABLE 6.1.:Water balance calculations:

Formulas		
Outside the growing season	During the growing season	ΣP-D-E
Penman	EH1	80.4
Penman	EH2	76.8
Penman	EH3	79.0
Thom-Oliver	EH1	0.1
Thom-Oliver	EH2	-2.0
Thom-Oliver	EH3	-1.3
Makkink A	EH1	-15.4
Makkink A	EH2	-15.6
Makkink A	EH3	-17.6
Makkink B	EH1	24.9
Makkink B	EH2	18.3
Makkink B	EH3	23.0
Thom-Oliver	ETA1	8.6
Thom-Oliver	EH2/ ETA2	-20.7
Thom-Oliver	ETA3	22.3

For the last case,ETA1,ETA2,ETA3 were used for the dry period going from the 15th of July to the 30th of August.

6.4.Analysis.

The calculated storage -4.3 has to be compared with the numbers recorded in table 6.1.

-The formula of Thom and Oliver yields remarkably good results(between 0.1 and -2.0).This confirms the results reported by Stricker (1981).

-The formulation of Makkink(1) overestimates evapotranspiration slightly but these of Makkink(2) and Penman underestimate it.

-These calculations yield results which are in good agreement with found in section 5.2.3. for the relationships existing among the different methods available for computing the potential evapotranspiration.

-Using one or another temperature gradient for the calculation of the actual evpotranspiration by the indirect method does not produce a big change.No significant difference can be seen as the comparative analysis showed.
The indirect method seems thus to produce the best results among the three methods based on the profiles measurements,since the Bowen ratio and direct method are giving systematic lower results.This would result in a larger difference in the water balance calculations.

-Using the results computed from the advection-aridity method for the actual evapotranspiration during a water-restricted period instead of the results calculated from the indirect method yields only acceptable results for the first equation.This method,easier to use than the methods based on the energy balance and the measurements of wind velocity and temperature profiles,can thus be very useful to calculate actual evapotranspiration during dry periods.

The biweekly values of soil moisture content would have enable to make the calculations of the water balance over shorter periods,and to distinguish periods according to the amount of precipitation.

Nevertheless,it can be concluded that for the conditions of this watershed,the formulations of Thom and Oliver and the energy balance yield the best result for respectively the potential and the actual evapotranspiration.

CHAPTER 7 : CONCLUSION

This study enables to draw some conclusions about the different methods which can be used for the calculation of evapotranspiration.These conclusions are applicable to Hupselse Beek area, but also to any catchment with similar conditions (temperate climate,major grassland).

-Outside the growing season,a good approach of the actual evapotranspiration is produced by the potential evapotranspiration concept especially by the formulation of Thom and Oliver and Makkink (standard formulation).

-During the growing season,the actual evapotranspiration has to be calculated.It can be done by the energy budget equation and the sensible heat flux calculated from the wind speed and temperature profiles.This method,which requires an accuracy of measurements relatively easy to reach and is easily settled,yields good values of evapotranspiration.

-Two other methods,based on the same theory,can be used but they are instrumentally more difficult to manage and produce obviously less reliable results.The Bowen ratio method yields acceptable results but it fails around sunrise,sunset and sometimes at night.It can be noted that the Bowen ratio method and the energy balance method which require only two profile measurements (wet and dry-bulb temperature for the Bowen ratio and wind speed and dry-bulb temperature measurement for the energy balance method)are more reliable than the direct method which uses the three profiles.

-For a dry period,results from the advection-aridity method are for one formulation in fair agreement with the results obtained by the energy balance method.Thus,according to the equipments which can be settled, different methods can be used to compute evapotranspiration.If only meteorological data are available,reliable values of the actual evapotranspiration can be calculated.

REFERENCES:

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BRUIN,H.A.R. DE (1987). From Penman to Makkink . Evaporation and weather.TNO: Committee on Hydrological research,The Hague.Proceedings and information No 39:5-31.

BRUTSAERT,W. (1982).Evaporation into the atmosphere, Theory, History,and Applications.D Reidel publishing company,Dordrecht.

BRUTSAERT,W. and STRICKER,H. (1979).An advection-aridity approach to estimate Actual Regional Evapotranspiration.Water Resources Research, Vol 15,No 2:443-450.

FRITSCHEN,L.J. (1981).The vertical heat fluxes of heat and moisture at a vegetated land surface,in Land surface processes in atmospheric general circulation models.Papers presented at the World Climate Research Programme study conference,in Greenbelt,Maryland,5 to 10 January 1981.Eagleson,Cambridge,Massachusetts.

FUCHS,M. and TANNER,C.B. (1970).Error analysis of Bowen ratios measured by differential psychrometry.Agricultural meteorology,7:329-334.

GRANT,D.R. (1975).Comparisons of evaporation measurements using different methods. Quarterly journal of the Royal Meteorological Society, No 101:543-550.

HOLTSLAG,A.A.M (1987).Surface fluxes and boundary layer scaling.Koninklijk nederlands meteorologisch instituut,De Bilt,scientific report WR-nr87-2

HOPMANS,J.W. and STRICKER J.N.M. (1987).Soil hydraulic properties in the study area Hupselse Beek as obtained from different scales of observation:an overview.Landbouw Universiteit Wageningen,Hydraulica and Afvoerhydrologie ,publication No 78.

LABORDE,J.P. (1982).Elements d'hydrologie de surface :Tome 1:Le milieu hydrologique,l'acquisition des donnees.Cours ENITRTS,Strasbourg.

MOLEN,W.H. VAN DER (1983).Agrohydrology,MSc course in soil science and water management.Agricultural University,Wageningen,The Netherlands.

MONTEITH,J.L. (1973).Principles of Environmental Physics.Contemporary biology.Edward Arnold,London.

PERRIER,A. (1981).Land surface processes : vegetation,in Land surface processes in atmospheric general circulation models.Papers presented at the World Climate Programme study conference,in Greenbelt,Maryland,5 to 10 January 1981.Eagleson,Cambridge,Massachusetts.

PRIESTLEY,C.H.B. and TAYLOR,R.J. (1972).On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters.

REITSMA,T.(1978):Wind profile measurements above a maize crop.PUDOC(Centre for agricultural publishing and documentation)Wageningen.

STRICKER,H. and BRUTSAERT,W.(1978).Actual evapotranspiration over a summer period in the 'Hupsel catchment'.Journal of hydrology,39:139-157.

STRICKER,J.N.M. (1981).Methods of estimating evapotranspiration from meteorological data and their applicability in hydrology.Evaporation in relation to hydrology.TNO:Committee for hydrological research,The Hague. Proceedings and information No 28:59:77.

TARDY,Y. (1986).Le cycle de l'eau.Masson,Paris.

THOM,A.S. and OLIVER,H.R. (1977).On Penman's equation for estimating regional evaporation. Quaterly journal of the Royal Meteorological Society,Vol 103,No 436:345-373.

WARMERDAM,P.M.M. (1985).Rainfall-runoff modelling in the Hupselse Beek area.Seminar 1 to 3 october 1985.Warsaw Agriculture University,Faculty of land reclamation.

WARMERDAM,P.M.M and STRICKER,J.N.M.and KOLE,J.W (1982).Current research in the experimental catchment Hupselse Beek,in the Netherlands.In Hydrological research basins and their use in water resources planning,Vol 1. Bern.

APPENDIX

A.1.Text of the program EVAPO.FOR:

```
      PROGRAM EVAPO
C     ****************************************************
C     THIS PROGRAM IS CALCULATING THE SENSIBLE HEAT FLUX
C     AND THE EVAPOTRANSPIRATION FROM 20 MINUTES-DATA
C     MEASURED DURING 1983
C     ****************************************************

      INTEGER DATE(4464)
      INTEGER Rg(4464),Rn(4464),G1(4464),G2(4464)
      INTEGER D13(4464),D3(4464),D73(4464),D17(4464)
      INTEGER W13(4464),W3(4464),W73(4464),W17(4464)
      INTEGER U2(4464),U3(4464),U9(4464),U23(4464),U93(4464)
      INTEGER Ts(4464),RH(4464),SD(4464)
      INTEGER WD(4464),SHF(4464),SWRO(4464)
      INTEGER M,M1,M2,M3
      INTEGER CT

      REAL RAIN(4464)
      REAL DL1(4464)
      REAL H1(4464),H2(4464),H3(4464),H5(4464),H6(4464),H7(4464)
      REAL E1(4464),E2(4464),E3(4464)
      REAL BETA1(4464)
      REAL EB1(4464),EB2(4464),EB3(4464)
      REAL K,G,CP,ZOM,ZOH,DH,GAMMA
      REAL UST1(4464),UST2(4464),UST3(4464)
      REAL UST5(4464),UST6(4464),UST7(4464)
      REAL HBETA,BETA2,BETA3
      REAL DL5,DL6,DL7
      REAL D03,SLD,HDL,HL,EH
      REAL KSI1,KSI2,KSI3,KSI4,PSI1,PSI2,PSI3,PSI4
      REAL RHO,DELTA,BB,DIFF
      REAL XH1,XH2,XM1,XM2
      REAL AA,AS,AT,AU,AV


C     H denotes the sensible heat flux
C     EB denotes the latent heat flux calculated by the Bowen
C     ratio method
C     E denotes the latent heat flux calculated directly from
C     the profiles

C     All these signs are followed by a figure related to the
C     considered level:
C     .1 or 5 for the lower level:1.30-3.15m
C     .2 or 6 for the upper level:3.15-7.14m
C     .3 or 7 for the global level:1.30-7.14m
C     SHF denotes the soil heat flux

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      OPEN(2,FILE='C:\INTERM\JULAUG83.DAT',STATUS='OLD')
      OPEN(3,FILE='D:\EVAP2083\JULAUG83.DAT',STATUS='NEW')
```

```
C      DEFINITION OF THE CONSTANTS:
C      ----------------------------
C      CP=SPECIFIC HEAT:JOULE/KG.K
       CP=1.01*10**3

C      G=GRAVITY ACCELERATION:M/S2
       G=9.81

C      K=VAN KARMAN CONSTANT
       K=0.41

C      GAMMA=PSYCHROMETRIC CONSTANT:MB/K
       GAMMA=0.655

C      DH=DISPLACEMENT HEIGHT FOR GRASS:M
       DH=0.05

C      ZOM=ROUGHNESS LENGTH FOR GRASS FOR MOMENTUM:M
       ZOM=0.01


       DO 10 I=1,4464

       READ(1,15) DATE(I),Rg(I),Rn(I),RAIN(I),G1(I),G2(I),D13(I),
      &D3(I),D73(I),W13(I),W3(I),W73(I),U2(I),U3(I),U9(I),Ts(I),RH(I),
      &SD(I),WD(I),SHF(I),SWRO(I)

 15    FORMAT(I10,1X,2I6,F6.2,17I6)

       READ(2,16)H1(I),H2(I),H3(I),UST1(I),UST2(I),UST3(I),DL1(I)
 16    FORMAT(3F6.1,3F6.3,F8.1)

C      CALCULATION OF THE WIND VELOCITY DIFFERENCE BETWEEN 2.14M
C      AND 3.97M
       IF((U2(I).NE.9999).AND.(U3(I).NE.9999))THEN
          U23(I)=U2(I)-U3(I)
       ELSE
          U23(I)=9999
       ENDIF

C      CALCULATION OF THE WIND VELOCITY DIFFERENCE BETWEEN 9.48M
C      AND 3.97M
       IF((U9(I).NE.9999).AND.(U3(I).NE.9999))THEN
          U93(I)=U9(I)-U3(I)
       ELSE
          U93(I)=9999
       ENDIF


C      CALCULATION OF DRY BULB TEMPERATURE DIFFERENCE BETWEEN 1.3M
C      AND 7.14M
       IF((D13(I).NE.9999).AND.(D73(I).NE.9999))THEN
          D17(I)=D13(I)-D73(I)
       ELSE
          D17(I)=9999
       ENDIF


C      CALCULATION OF THE WET BULB TEMPERATURE DIFFERENCE BETWEEN
C      1.3M AND 7.14M
       IF((W13(I).NE.9999).AND.(W73(I).NE.9999))THEN
```

```
      W17(I)=W13(I)-W73(I)
   ELSE
      W17(I)=9999
   ENDIF

C  CALCULATION OF THE DENSITY OF THE AIR:RHO:KG/M3
   RHO=29.48*10.0**2/(8.31*((D3(I)/10)+273.15))


C  CALCULATIONS OF THE SENSIBLE HEAT FLUXES:
C  *****************************************


C  CALCULATIONS WITH THE SECOND TEMPERATURE DIFFERENCES:
C
C  W13,W3,W73,W17
C
C  FROM THE 23rd OF JUNE AT 14h00 TO THE 30th OF JUNE AT 12h10,
C  FROM THE 13th OF JULY AT 11h00 TO THE 20th OF JULY AT 12h20,
C  THESE MEASUREMENTS ARE WET-BULB TEMPERATURE DIFFERENCES.
C  SO EVAPOTRANSPIRATION CAN BE CALCULATED WITH THE BOWEN RATIO.
C  WHEN THE MEASUREMENTS ARE DRY-BULB TEMPERATURE DIFFERENCES,
C  ANOTHER CALCULATION OF THE SENSIBLE HEAT FLUX IS MADE.

   IF((DATE(I).GE.831741440).AND.(DATE(I).LE.831811240))GO TO 240
   IF((DATE(I).GE.831941100).AND.(DATE(I).LE.832011220))GO TO 240

C  SECOND CALCULATION OF THE SENSIBLE HEAT FLUXES:
C  ***********************************************

C  THE EVAPOTRANSPIRATION CAN'T BE CALCULATED SO E1,E2,E3,EB1,
C  EB2,EB3,BETA1,BETA2,BETA3 ARE MISSING VALUES:888
   E1(I)=888.
   E2(I)=888.
   E3(I)=888.
   EB1(I)=888.
   EB2(I)=888.
   EB3(I)=888.
   BETA1(I)=888.
   BETA2=888.
   BETA3=888.


C  SENSIBLE HEAT FLUX FOR 1.30M-3.15M:
C  ***********************************


   IF(W13(I).GT.500) GO TO 948

C  ADIABATIC CORRECTION OF W13:
   W13(I)=W13(I)-2

C  CALCULATION WHEN THE WIND VELOCITY IS GREATER THAN 1.50M/S:
C  -----------------------------------------------------------
   IF(U3(I).LE.150) GO TO 791

   IF(U23(I).EQ.9999) GO TO 948
   IF(W13(I)) 760,770,780
```

```
C     760:STABLE ATMOSPHERE
C     ---------------------
 760  SLD=100000.
      PSI1=0.
      PSI2=0.
      PSI3=0.
      PSI4=0.
      M=0

 762  UST5(I)=K*(-U23(I)*0.01)/(ALOG((3.970-DH)/(2.140-DH))
     &-PSI1+PSI2)
      H5(I)=0.01*W13(I)*UST5(I)*RHO*CP*K/(ALOG((3.150-DH)/(1.30-DH))
     &-PSI3+PSI4)

      HDL=H5(I)
      HL=HDL/(CP*((0.1*W3(I))+273))
      DL5=-(UST5(I)**3*RHO)/(K*G*HL)

      DIFF=ABS(DL5-SLD)


      KSI1=(3.970-DH)/DL5
      KSI2=(2.140-DH)/DL5
      KSI3=(3.150-DH)/DL5
      KSI4=(1.30-DH)/DL5

      PSI1=-(0.7*KSI1+0.75*(KSI1-5/0.35)*EXP(-0.35*KSI1)+0.75/0.07)
      PSI2=-(0.7*KSI2+0.75*(KSI2-5/0.35)*EXP(-0.35*KSI2)+0.75/0.07)
      PSI3=-(0.7*KSI3+0.75*(KSI3-5/0.35)*EXP(-0.35*KSI3)+0.75/0.07)
      PSI4=-(0.7*KSI4+0.75*(KSI4-5/0.35)*EXP(-0.35*KSI4)+0.75/0.07)

      IF (DIFF.LE.0.1) GO TO 945

      M=M+1
      IF (M.GT.20) GO TO 948

      SLD=DL5
      GO TO 762


C     770:NEUTRAL ATMOSPHERE
C     ----------------------

 770  H5(I)=0.
      DL5=0.
      M=0

      UST5(I)=K*(-U23(I)*0.01)/ALOG((3.970-DH)/(2.140-DH))

      GO TO 950


C     780:UNSTABLE ATMOSPHERE
C     -----------------------

 780  SLD=-100000.
      M=0
      PSI1=0.
      PSI2=0.
      PSI3=0.
      PSI4=0.
```

```
782  UST5(I)=K*(-U23(I)*0.01)/(ALOG((3.970-DH)/(2.140-DH))
    £-PSI1+PSI2)
     H5(I)=0.01*W13(I)*UST5(I)*RHO*CP*K/(ALOG((3.150-DH)/(1.30-DH))
    £-PSI3+PSI4)

     HDL=H5(I)
     HL=HDL/(CP*((0.1*W3(I))+273))
     DL5=-UST5(I)**3*RHO/(K*G*HL)

     DIFF=ABS(DL5-SLD)

     XM1=(1.-16.*(3.97-DH)/DL5)**0.25
     XM2=(1.-16.*(2.14-DH)/DL5)**0.25
     XH1=(1.-16.*(3.15-DH)/DL5)**0.25
     XH2=(1.-16.*(1.30-DH)/DL5)**0.25

     PSI1=2.*ALOG((1.+XM1)/2.)+ALOG((1.+XM1**2)/2.)
    £-2.*ATAN(XM1)+3.1416/2.
     PSI2=2.*ALOG((1.+XM2)/2.)+ALOG((1.+XM2**2)/2.)
    £-2.*ATAN(XM2)+3.1416/2.
     PSI3=2.*ALOG((1.+XH1**2)/2.)
     PSI4=2.*ALOG((1.+XH2**2)/2.)

     IF (DIFF.LE.0.1) GO TO 945

     M=M+1
     IF(M.GT.20) GO TO 948

     SLD=DL5
     GO TO 782

C    CALCULATION WHEN THE WIND VELOCITY IS LOWER THAN 1.50M/S:
C    ----------------------------------------------------------
791  IF(U3(I).EQ.9999) GO TO 948

     IF(W13(I)) 790,800,810

C    790:STABLE ATMOSPHERE
C    ---------------------

790  SLD=100000.
     PSI1=0.
     PSI3=0.
     PSI4=0.
     M=0

792  UST5(I)=K*(U3(I)*0.01)/(ALOG((3.970-DH)/(ZOM))-PSI1)
     H5(I)=0.01*W13(I)*UST5(I)*RHO*CP*K/(ALOG((3.150-DH)/(1.30-DH))
    £-PSI3+PSI4)

     HDL=H5(I)
     HL=HDL/(CP*((0.1*W3(I))+273))
     DL5=-(UST5(I)**3*RHO)/(K*G*HL)

     DIFF=ABS(DL5-SLD)

     KSI1=(3.970-DH)/DL5
     KSI3=(3.150-DH)/DL5
     KSI4=(1.30-DH)/DL5
```

```
      PSI1=-(0.7*KSI1+0.75*(KSI1-5/0.35)*EXP(-0.35*KSI1)+0.75/0.07)
      PSI3=-(0.7*KSI3+0.75*(KSI3-5/0.35)*EXP(-0.35*KSI3)+0.75/0.07)
      PSI4=-(0.7*KSI4+0.75*(KSI4-5/0.35)*EXP(-0.35*KSI4)+0.75/0.07)

      IF (DIFF.LE.0.1) GO TO 945

      M=M+1
      IF (M.GT.20) GO TO 948

      SLD=DL5
      GO TO 792

C     800:NEUTRAL ATMOSPHERE
C     ----------------------
 800  H5(I)=0.
      DL5=0.
      M=0

      UST5(I)=K*(U3(I)*0.01)/ALOG((3.970-DH)/(ZOM))

      GO TO 950

C     810:UNSTABLE ATMOSPHERE
C     -----------------------

 810  SLD=-100000.
      M=0
      PSI1=0.
      PSI3=0.
      PSI4=0.

 812  UST5(I)=K*(U3(I)*0.01)/(ALOG((3.970-DH)/(ZOM))-PSI1)
      H5(I)=0.01*W13(I)*UST5(I)*RHO*CP*K/(ALOG((3.150-DH)/(1.30-DH))
     £-PSI3+PSI4)

      HDL=H5(I)
      HL=HDL/(CP*((0.1*W3(I))+273))
      DL5=-UST5(I)**3*RHO/(K*G*HL)

      DIFF=ABS(DL5-SLD)

      XM1=(1.-16.*(3.97-DH)/DL5)**0.25
      XH1=(1.-16.*(3.15-DH)/DL5)**0.25
      XH2=(1.-16.*(1.30-DH)/DL5)**0.25

      PSI1=2.*ALOG((1.+XM1)/2.)+ALOG((1.+XM1**2)/2.)
     £-2.*ATAN(XM1)+3.1416/2.
      PSI3=2.*ALOG((1.+XH1**2)/2.)
      PSI4=2.*ALOG((1.+XH2**2)/2.)

      IF (DIFF.LE.0.1) GO TO 945

      M=M+1
      IF(M.GT.20) GO TO 948

      SLD=DL5
      GO TO 812

 945  CONTINUE
```

```
      M1=M

      GO TO 950

 948  H5(I)=999
      UST5(I)=9.99
      DL5=999
      M1=0
      GO TO 950

C     SENSIBLE HEAT FLUX FOR 3.15M-7.14M:
C     **********************************

 950  IF(W73(I).GT.500.) GO TO 989

C     ADIABATIC CORRECTION OF W73:
      W73(I)=W73(I)+4

      BB=-W73(I)

C     CALCULATION WHEN THE WIND VELOCITY IS GREATER THAN 1.5M/S:
C     -----------------------------------------------------------
      IF(U3(I).LE.150) GO TO 821

      IF(U93(I).EQ.9999) GO TO 989

      IF (BB) 960,970,980

C     960:STABLE ATMOSPHERE
C     --------------------

 960  SLD=100000.
      PSI1=0.
      PSI2=0.
      PSI3=0.
      PSI4=0.
      M=0

 962  UST6(I)=K*(U93(I)*0.01   )/(ALOG((9.48-DH)/(3.97-DH))
     &-PSI1+PSI2)
      H6(I)=-0.01*W73(I)*UST6(I)*RHO*CP*K/(ALOG((7.14-DH)/(3.15-DH))
     &-PSI3+PSI4)

      HDL=H6(I)
      HL=HDL/(CP*((0.1*W3(I))+273))
      DL6=-UST6(I)**3*RHO/(K*G*HL)

      DIFF=ABS(DL6-SLD)

      KSI1=(9.48-DH)/DL6
      KSI2=(3.97-DH)/DL6
      KSI3=(7.14-DH)/DL6
      KSI4=(3.15-DH)/DL6

      PSI1=-(0.7*KSI1+0.75*(KSI1-5/0.35)*EXP(-0.35*KSI1)+0.75/0.07)
      PSI2=-(0.7*KSI2+0.75*(KSI2-5/0.35)*EXP(-0.35*KSI2)+0.75/0.07)
      PSI3=-(0.7*KSI3+0.75*(KSI3-5/0.35)*EXP(-0.35*KSI3)+0.75/0.07)
      PSI4=-(0.7*KSI4+0.75*(KSI4-5/0.35)*EXP(-0.35*KSI4)+0.75/0.07)

      IF(DIFF.LE.0.1) GO TO 988
```

```
      M=M+1
      IF(M.GT.20) GO TO 989

      SLD=DL6
      GO TO 962

C     970:NEUTRAL ATMOSPHERE
C     ----------------------

 970  H6(I)=0.
      DL6=0.
      M=0

      UST6(I)=K*(U93(I)*0.01)/ALOG((9.48-DH)/(3.97-DH))

      GO TO 990

C     UNSTABLE ATMOSPHERE
C     -------------------

 980  SLD=-100000.
      M=0
      PSI1=0.
      PSI2=0.
      PSI3=0.
      PSI4=0.

 982  UST6(I)=K*(U93(I)*0.01)/(ALOG((9.48-DH)/(3.97-DH))
     £-PSI1+PSI2)
      H6(I)=-0.01*W73(I)*UST6(I)*RHO*CP*K/(ALOG((7.14-DH)/(3.15-DH))
     £-PSI3+PSI4)

      HDL=H6(I)
      HL=HDL/(CP*((0.1*W3(I))+273))
      DL6=-(UST6(I)**3*RHO)/(K*G*HL)

      DIFF=ABS(DL6-SLD)

      XM1=(1.-16.*(9.48-DH)/DL6)**0.25
      XM2=(1.-16.*(3.97-DH)/DL6)**0.25
      XH1=(1.-16.*(7.14-DH)/DL6)**0.25
      XH2=(1.-16.*(3.15-DH)/DL6)**0.25

      PSI1=2.*ALOG((1.+XM1)/2.)+ALOG((1.+XM1**2)/2.)
     £-2.*ATAN(XM1)+3.1416/2.
      PSI2=2.*ALOG((1.+XM2)/2.)+ALOG((1.+XM2**2)/2.)
     £-2.*ATAN(XM2)+3.1416/2.
      PSI3=2.*ALOG((1.+XH1**2)/2.)
      PSI4=2.*ALOG((1.+XH2**2)/2.)

      IF(DIFF.LE.0.1) GO TO 988

      M=M+1
      IF(M.GT.20) GO TO 989

      SLD=DL6
      GO TO 982

C     CALCULATION WHEN THE WIND VELOCITY IS LOWER THAN 1.5M/S:
C     --------------------------------------------------------
 821  IF(U3(I).EQ.9999) GO TO 989
```

```
      IF (BB) 820,830,840

C     820:STABLE ATMOSPHERE
C     ---------------------

 820  SLD=100000.
      PSI1=0.
      PSI3=0.
      PSI4=0.
      M=0

 822  UST6(I)=K*(U3(I)*0.01)/(ALOG((3.97-DH)/(ZOM))-PSI1)
      H6(I)=-0.01*W73(I)*UST6(I)*RHO*CP*K/(ALOG((7.14-DH)/(3.15-DH))
     &-PSI3+PSI4)

      HDL=H6(I)
      HL=HDL/(CP*((0.1*W3(I))+273))
      DL6=-(UST6(I)**3*RHO)/(K*G*HL)

      DIFF=ABS(DL6-SLD)

      KSI1=(3.97-DH)/DL6
      KSI3=(7.14-DH)/DL6
      KSI4=(3.15-DH)/DL6

      PSI1=-(0.7*KSI1+0.75*(KSI1-5/0.35)*EXP(-0.35*KSI1)+0.75/0.07)
      PSI3=-(0.7*KSI3+0.75*(KSI3-5/0.35)*EXP(-0.35*KSI3)+0.75/0.07)
      PSI4=-(0.7*KSI4+0.75*(KSI4-5/0.35)*EXP(-0.35*KSI4)+0.75/0.07)

      IF(DIFF.LE.0.1) GO TO 988

      M=M+1
      IF(M.GT.20) GO TO 989

      SLD=DL6
      GO TO 822

C     830:NEUTRAL ATMOSPHERE
C     ----------------------

 830  H6(I)=0.
      DL6=0.
      M=0

      UST6(I)=K*(U3(I) * 0.01)/ALOG((3.97-DH)/(ZOM))

      GO TO 990


C     840:UNSTABLE ATMOSPHERE
C     -----------------------

 840  SLD=-100000.
      M=0
      PSI1=0.
      PSI3=0.
      PSI4=0.

 842  UST6(I)=K*(U3(I) * 0.01)/(ALOG((3.97-DH)/(ZOM))-PSI1)
      H6(I)=-0.01*W73(I)*UST6(I)*RHO*CP*K/(ALOG((7.14-DH)/(3.15-DH))
```

```
     £-PSI3+PSI4)

      HDL=H6(I)
      HL=HDL/(CP*((0.1*W3(I))+273))
      DL6=-UST6(I)**3*RHO/(K*G*HL)

      DIFF=ABS(DL6-SLD)

      XM1=(1.-16.*(3.97-DH)/DL6)**0.25
      XH1=(1.-16.*(7.14-DH)/DL6)**0.25
      XH2=(1.-16.*(3.15-DH)/DL6)**0.25

      PSI1=2.*ALOG((1.+XM1)/2.)+ALOG((1.+XM1**2)/2.)
     £-2.*ATAN(XM1)+3.1416/2.
      PSI3=2.*ALOG((1.+XH1**2)/2.)
      PSI4=2.*ALOG((1.+XH2**2)/2.)

      IF(DIFF.LE.0.1) GO TO 988

      M=M+1
      IF(M.GT.20) GO TO 989

      SLD=DL6
      GO TO 842


 988  CONTINUE

      M2=M

      GO TO 990

 989  H6(I)=999
      DL6=999
      UST6(I)=9.99
      M2=0
      GO TO 990

C     SENSIBLE HEAT FLUX FOR 1.30M-7.14M:
C     ***********************************

 990  IF(W17(I).GT.500)GO TO 995

C     CALCULATION WHEN THE WIND VELOCITY IS GREATER THAN 1.50M/S:
C     ------------------------------------------------------------

      IF(U3(I).LE.150)GO TO 981

      IF((U93(I).EQ.9999).OR.(U23(I).EQ.9999)) GO TO 995
      IF((U93(I)-U23(I)).LE.0)GO TO 981

C     ADIABATIC CORRECTION OF W17:
      W17(I)=W17(I)-6
      IF (W17(I)) 992,994,996

C     992:STABLE ATMOSPHERE
C     ---------------------

 992  SLD=100000.
      PSI1=0.
      PSI2=0.
```

```
      PSI3=0.
      PSI4=0.
      M=0

993   UST7(I)=K*(U93(I)-U23(I))*0.01/(ALOG((9.48-DH)/(2.14-DH))
     £-PSI1+PSI2)
      H7(I)=0.01*W17(I)*UST7(I)*RHO*CP*K/(ALOG((7.14-DH)/(1.3-DH))
     £-PSI3+PSI4)

      HDL=H7(I)
      HL=HDL/(CP*((0.1*W3(I))+273))
      DL7=-(UST7(I)**3*RHO)/(K*G*HL)

      DIFF=ABS(DL7-SLD)

      KSI1=(9.48-DH)/DL7
      KSI2=(2.14-DH)/DL7
      KSI3=(7.14-DH)/DL7
      KSI4=(1.30-DH)/DL7

      PSI1=-(0.7*KSI1+0.75*(KSI1-5/0.35)*EXP(-0.35*KSI1)+0.75/0.07)
      PSI2=-(0.7*KSI2+0.75*(KSI2-5/0.35)*EXP(-0.35*KSI2)+0.75/0.07)
      PSI3=-(0.7*KSI3+0.75*(KSI3-5/0.35)*EXP(-0.35*KSI3)+0.75/0.07)
      PSI4=-(0.7*KSI4+0.75*(KSI4-5/0.35)*EXP(-0.35*KSI4)+0.75/0.07)

      IF(DIFF.LE.0.1) GO TO 998

      M=M+1
      IF(M.GT.20) GO TO 995

      SLD=DL7
      GO TO 993

C     994:NEUTRAL ATMOSPHERE
C     ----------------------

 994  H7(I)=0.
      DL7=0.
      M=0

      UST7(I)=K*(U93(I)-U23(I))*0.01/ALOG((9.48-DH)/(2.14-DH))

      GO TO 999

C     996:UNSTABLE ATMOSPHERE
C     -----------------------

 996  SLD=-100000.
      M=0
      PSI1=0.
      PSI2=0.
      PSI3=0.
      PSI4=0.

 997  UST7(I)=K*(U93(I)-U23(I))*0.01/(ALOG((9.48-DH)/(2.14-DH))
     £-PSI1+PSI2)
      H7(I)=0.01*W17(I)*UST7(I)*RHO*CP*K/(ALOG((7.14-DH)/(1.3-DH))
     £-PSI3+PSI4)

      HDL=H7(I)
      HL=HDL/(CP*((0.1*W3(I))+273))
```

```
      DL7=-(UST7(I)**3*RHO)/(K*G*HL)

      DIFF=ABS(DL7-SLD)

      XM1=(1.-16.*(9.48-DH)/DL7)**0.25
      XM2=(1.-16.*(2.14-DH)/DL7)**0.25
      XH1=(1.-16.*(7.14-DH)/DL7)**0.25
      XH2=(1.-16.*(1.3-DH)/DL7)**0.25

      PSI1=2.*ALOG((1.+XM1)/2.)+ALOG((1.+XM1**2)/2.)
     £-2.*ATAN(XM1)+3.1416/2.
      PSI2=2.*ALOG((1.+XM2)/2.)+ALOG((1.+XM2**2)/2.)
     £-2.*ATAN(XM2)+3.1416/2.
      PSI3=2.*ALOG((1.+XH1**2)/2.)
      PSI4=2.*ALOG((1.+XH2**2)/2.)

      IF(DIFF.LE.0.1) GO TO 998

      M=M+1
      IF(M.GT.20) GO TO 995

      SLD=DL7
      GO TO 997

C     CALCULATION WHEN THE WIND VELOCITY IS LOWER THAN 1.5M/S:
C     -------------------------------------------------------
 981  IF(U3(I).EQ.9999) GO TO 995

      W17(I)=W17(I)-6
      IF (W17(I)) 983,985,986

C     983:STABLE ATMOSPHERE:
C     ---------------------

 983  SLD=100000.
      PSI1=0
      PSI3=0.
      PSI4=0.
      M=0

 984  UST7(I)=K*U3(I)*0.01/(ALOG((3.97-DH)/(ZOM))-PSI1)
      H7(I)=0.01*W17(I)*UST7(I)*RHO*CP*K/(ALOG((7.14-DH)/(1.3-DH))
     £-PSI3+PSI4)

      HDL=H7(I)
      HL=HDL/(CP*((0.1*W3(I))+273))
      DL7=-UST7(I)**3*RHO/(K*G*HL)

      DIFF=ABS(DL7-SLD)

      KSI1=(3.97-DH)/DL7
      KSI3=(7.14-DH)/DL7
      KSI4=(1.30-DH)/DL7

      PSI1=-(0.7*KSI1+0.75*(KSI1-5/0.35)*EXP(-0.35*KSI1)+0.75/0.07)
      PSI3=-(0.7*KSI3+0.75*(KSI3-5/0.35)*EXP(-0.35*KSI3)+0.75/0.07)
      PSI4=-(0.7*KSI4+0.75*(KSI4-5/0.35)*EXP(-0.35*KSI4)+0.75/0.07)

      IF(DIFF.LE.0.1) GO TO 998
```

```
      M=M+1
      IF(M.GT.20) GO TO 995

      SLD=DL7
      GO TO 984

C     985:NEUTRAL ATMOSPHERE:
C     -----------------------

 985  H7(I)=0.
      DL7=0.
      M=0

      UST7(I)=K*U3(I)*0.01/ALOG((3.97-DH)/(ZOM))
      P5=UST7(I)/ALOG((7.14-DH)/(1.3-DH))

      GO TO 999

C     985:UNSTABLE ATMOSPHERE:
C     ------------------------

 986  SLD=-100000.
      M=0
      PSI1=0.
      PSI2=0.
      PSI3=0.
      PSI4=0.

 987  UST7(I)=K*U3(I)*0.01/(ALOG((3.97-DH)/(ZOM))-PSI1)
      H7(I)=0.01*W17(I)*UST7(I)*RHO*CP*K/(ALOG((7.14-DH)/(1.3-DH))
     £-PSI3+PSI4)

      HDL=H7(I)
      HL=HDL/(CP*((0.1*W3(I))+273))
      DL7=-(UST7(I)**3*RHO)/(K*G*HL)

      DIFF=ABS(DL7-SLD)

      XM1=(1.-16.*(3.97-DH)/DL7)**0.25
      XH1=(1.-16.*(7.14-DH)/DL7)**0.25
      XH2=(1.-16.*(1.3-DH)/DL7)**0.25

      PSI1=2.*ALOG((1.+XM1)/2.)+ALOG((1.+XM1**2)/2.)
     £-2.*ATAN(XM1)+3.1416/2.
      PSI3=2.*ALOG((1.+XH1**2)/2.)
      PSI4=2.*ALOG((1.+XH2**2)/2.)

      IF(DIFF.LE.0.1) GO TO 998

      M=M+1
      IF(M.GT.20) GO TO 995

      SLD=DL7
      GO TO 987

 998  CONTINUE

      M3=M

      GO TO 999
```

```
 995  H7(I)=999
      DL7=999
      UST7(I)=9.99
      M3=0

 999  GO TO 650


C     CALCULATIONS WITH THE WET-BULB TEMPERATURE DIFFERENCES:
C     ********************************************************


C     THE SECOND CALCULATIONS OF THE SENSIBLE HEAT FLUX ARE NOT
C     MADE SO H5,H6,H7,UST5,UST6,UST7 ARE MISSING VALUES:888
 240  H5(I)=888.
      H6(I)=888.
      H7(I)=888.
      UST5(I)=8.88
      UST6(I)=8.88
      UST7(I)=8.88

C     CALCULATION OF DELTA:SLOPE OF THE SATURATION WATER VAPOR
C                          PRESSURE CURVE (MB/K)

      AA=4.58
      AS=0.333
      AT=0.01065
      AU=0.0001873
      AV=0.00000322
      DELTA=(AS+(2.*AT*0.1*W3(I))+(3.*AU*(0.1*W3(I))**2)+(4.*AV*
     &(0.1*W3(I))**3))*1.333

C     ADIABATIC CORRECTIONS
      D17(I)=D17(I)-6
      D13(I)=D13(I)-2
      D73(I)=D73(I)+4

      BB=-D73(I)

C     CALCULATIONS OF THE LATENT HEAT FLUXES:
C     ****************************************

C     FROM THE PROFILES:
C     ******************

C     LATENT HEAT FLUX FOR1.30M-3.15M:
C     *********************************

      IF(D13(I).GT.500) GO TO 275
      IF(W13(I).GT.500) GO TO 275

      EH=((DELTA+GAMMA)*W13(I)*0.01-GAMMA*D13(I)*0.01)/GAMMA
      IF(D13(I).EQ.0)THEN
         E1(I)=(UST1(I)*RHO*CP*K*EH)/ALOG((3.15-DH)/(2.14-DH))
      ELSE
         E1(I)=(H1(I)/(0.01*D13(I)))*EH
      END IF
      GO TO 280
```

```
 275  E1(I)=999.

 280  CONTINUE


C     LATENT HEAT FLUX FOR 3.15M-7.14M:
C     *********************************

      IF(W73(I).GT.500) GO TO 398
      IF(D73(I).GT.500) GO TO 398

      EH=((DELTA+GAMMA)*(-W73(I)*0.01)-(GAMMA*BB*0.01))/GAMMA

      IF(D73(I).EQ.0)THEN
         E2(I)=(UST2(I)*RHO*CP*K*EH)/ALOG((7.14-DH)/(3.15-DH))
      ELSE
         E2(I)=(H2(I)/(0.01*BB))*EH
      END IF
      GO TO 330

 398  E2(I)=999.

 330  CONTINUE


C     LATENT HEAT FLUX FOR 1.30M-7.14M:
C     *********************************

      IF(W17(I).GT.500) GO TO 396
      IF(D17(I).GT.500) GO TO 396

      EH=((DELTA+GAMMA)*W17(I)*0.01-GAMMA*W17(I)*0.01)/GAMMA

      IF(D17(I).EQ.0)THEN
         E3(I)=(UST3(I)*RHO*CP*K*EH)/ALOG((7.14-DH)/(1.30-DH))
      ELSE
         E3(I)=(H3(I)/(0.01*D17(I)))*EH
      END IF
      GO TO 399

 396  E3(I)=999.

 399  CONTINUE


C     CALCULATIONS WITH THE BOWEN RATIOS:
C     ***********************************

C     BOWEN RATIO OVER 1.30M-3.150M:
C     ------------------------------

      IF(W13(I).GT.500) GO TO 480
      IF(D13(I).GT.500) GO TO 480
      IF(Rn(I).EQ.9999) GO TO 480
      IF(SHF(I).EQ.9999) GO TO 480

 445  IF((D13(I).EQ.0).AND.(W13(I).EQ.0)) GO TO 460
      IF (D13(I).EQ.0) GO TO 450
      IF (W13(I).EQ.0) GO TO 460

      HBETA=((GAMMA+DELTA)/GAMMA)*W13(I)/D13(I)
```

```
      IF((HBETA.GT.-1.0).AND.(HBETA.LT.1.0)) GO TO 480

      BETA1(I)=1./(HBETA-1.)
      EB1(I)=(Rn(I)-SHF(I))/(1.+BETA1(I))

      GO TO 500

 450  EB1(I)=Rn(I)-SHF(I)
      BETA1(I)=0.0

      GO TO 500

 460  EB1(I)=0.0
      BETA1(I)=1000.

      GO TO 500

 480  BETA1(I)=999.
      EB1(I)=999.

 500  CONTINUE

C     BOWEN RATIO OVER 3.150M-7.140M:
C     -------------------------------
      IF(W73(I).GT.500) GO TO 540
      IF(D73(I).GT.500) GO TO 540
      IF(Rn(I).EQ.9999) GO TO 540
      IF(SHF(I).EQ.9999) GO TO 540


      IF((D73(I).EQ.0).AND.(W73(I).EQ.0)) GO TO 530
      IF(D73(I).EQ.0) GO TO 520
      IF (W73(I).EQ.0) GO TO 530

      HBETA=((GAMMA+DELTA)/GAMMA)*(-W73(I))/(-D73(I))

      IF ((HBETA.GT.-1.0).AND.(HBETA.LT.1.0)) GO TO  540
      BETA2=1./(HBETA-1.)

      EB2(I)=(Rn(I)-SHF(I))/(1.+BETA2)

      GO TO 550


 520  EB2(I)=Rn(I)-SHF(I)
      BETA2=0.0

      GO TO 550

 530  EB2(I)=0.0
      BETA2=1000.

      GO TO 550

 540  BETA2=999.
      EB2(I) =999.

 550  CONTINUE
```

```
C      BOWEN RATIO OVER 1.30-7.14M:
C      ----------------------------

       IF(D17(I).GT.500) GO TO 580
       IF(W17(I).GT.500) GO TO 580
       IF(Rn(I).EQ.9999) GO TO 580
       IF(SHF(I).EQ.9999) GO TO 580

       IF((W17(I).EQ.0).AND.(D17(I).EQ.0)) GO TO 570
       IF(W17(I).EQ.0) GO TO 570
       IF(D17(I).EQ.0) GO TO 560

       HBETA=((GAMMA+DELTA)/GAMMA)*W17(I)/D17(I)

       IF((HBETA.LT.1.0).AND.(HBETA.GT.-1.0)) GO TO 580

       BETA3=1./(HBETA-1.)
       EB3(I)=(Rn(I)-SHF(I))/(1.+BETA3)

       GO TO 650

 560   EB3(I)=Rn(I)-SHF(I)
       BETA3=0.

       GO TO 650

 570   EB3(I)=0.
       BETA3=1000.

       GO TO 650

 580   BETA3=999.
       EB3(I)=999.


 650   IF(ABS(H1(I)).GE.999.)H1(I)=999.
       IF(ABS(H2(I)).GE.999.)H2(I)=999.
       IF(ABS(H3(I)).GE.999.)H3(I)=999.
       IF(ABS(H5(I)).GE.999.)H5(I)=999.
       IF(ABS(H6(I)).GE.999.)H6(I)=999.
       IF(ABS(H7(I)).GE.999.)H7(I)=999.
       IF(ABS(E1(I)).GE.999.)E1(I)=999.
       IF(ABS(E2(I)).GE.999.)E2(I)=999.
       IF(ABS(E3(I)).GE.999.)E3(I)=999.
       IF(ABS(UST1(I)).GE.999.)UST1(I)=9.99
       IF(ABS(UST2(I)).GE.999.)UST2(I)=9.99
       IF(ABS(UST3(I)).GE.999.)UST3(I)=9.99
       IF(ABS(UST5(I)).GE.999.)UST5(I)=9.99
       IF(ABS(UST6(I)).GE.999.)UST6(I)=9.99
       IF(ABS(UST7(I)).GE.999.)UST7(I)=9.99
       IF(ABS(DL1(I)).GE.9999.)DL1(I)=9999.

 675   CONTINUE

C      WRITING THE RESULTS

       WRITE(3,1110)DATE(I),RAIN(I),Rn(I),SHF(I),H1(I),H2(I),H3(I),
      £UST1(I),UST2(I),UST3(I),E1(I),E2(I),E3(I),EB1(I),EB2(I),EB3(I)
```

```
     £WD(I)

1110 FORMAT(I10,2X,F6.2,2I6,3F8.0,3F8.2,6F8.0)

10   CONTINUE

     CLOSE(1)
     CLOSE(2)
     CLOSE(3)

     STOP

     END
```

A.2.Text of the program EVAPOT.FOR:

```
      PROGRAM EVAPOT

C     THIS PROGRAM IS CALCULATING THE EVAPOTRANSPIRATION WITH THE
C     ENERGY BUDGET EQUATION AND FROM THE VALUES OF THE NET RADIATION,
C     SOIL HEAT FLUX AND SENSIBLE HEAT FLUX


      INTEGER DATE(2232),Rn(2232),G(2232),WD(2232)
      REAL RAIN(2232)
      REAL H1(2232),H2(2232),H3(2232),H5(2232),H6(2232),H7(2232)
      REAL EH1(2232),EH2(2232),EH3(2232)
      REAL EH5(2232),EH6(2232),EH7(2232)
      REAL E1(2232),E2(2232),E3(2232)
      REAL EB1(2232),EB2(2232),EB3(2232)
      REAL UST1(2232),UST2(2232),UST3(2232)
      REAL UST5(2232),UST6(2232),UST7(2232),DL1(2232)
      REAL BETA1(2232)
      INTEGER CT
      INTEGER LEN(6)
      CHARACTER*12 RESN(6),EVAN(6)


C     H denotes the sensible heat flux
C     EH denotes the latent heat flux calculated with the energy
C        budget equation and sensible heat flux.
C     EB denotes the latent heat flux calculated by the Bowen
c     ratio method
C     E denotes the latent heat flux calculated directly from the
C     profiles

C     All these signs are followed by a figure related to the
C     considered level:
C     .1 or 5 for the lower level:1.30-3.15m
C     .2 or 6 for the upper level:3.15-7.14m
C     .3 or 7 for the global level:1.30-7.14m


      DATA LEN/2232,2160,2232,2232,2160,2232/
      DATA RESN/'RESMAY83.DAT','RESJUN83.DAT','RESJUL83.DAT',
     £'RESAUG83.DAT','RESEP83.DAT','RESOCT83.DAT'/
      DATA EVAN/'EVAMAY83.DAT','EVAJUN83.DAT','EVAJUL83.DAT',
     £'EVAAUG83.DAT','EVASEP83.DAT','EVAOCT83.DAT'/

      DO 5 L=1,6

      OPEN(1,FILE='E:\EVAP2083\'//RESN(L),STATUS='OLD')
      OPEN(2,FILE='E:\EVAP2083\'//EVAN(L),STATUS='NEW')

      CT=0

      DO 10 I=1,LEN(L)

      CT=CT+3
      IF(CT.GT.60)CT=3
```

```
      IF(CT.EQ.3)READ(1,1000)
 1000 FORMAT(/////)

      READ(1,1100)DATE(I),RAIN(I),Rn(I),G(I),H1(I),H2(I),H3(I),H5(I)
     £,H6(I),H7(I),UST1(I),UST2(I),UST3(I),UST5(I),UST6(I),UST7(I),
     £DL1(I),E1(I),E2(I),E3(I),EB1(I),EB2(I),EB3(I),BETA1(I),WD(I)

 1100 FORMAT(I10,2X,F6.2,2X,I4,2X,I4,3X,F5.0,2X,F5.0,2X,F5.0,2X,F5.0,
     £2X,F5.0,2X,F5.0/5X,F5.2,2X,F5.2,2X,F5.2,2X,F5.2,2X,F5.2,2X,F5.2,
     £2X,F8.1/5X,F5.0,2X,F5.0,2X,F5.0,2X,F5.0,2X,F5.0,2X,F5.0,2X,F7.2,
     £3X,I4)

      IF(Rn(I).EQ.9999)GO TO 200
      IF(G(I).EQ.9999)GO TO 200

      IF(H1(I).GE.777)THEN
         EH1(I)=999.
      ELSE
         EH1(I)=Rn(I)-G(I)-H1(I)
      END IF

      IF(H2(I).GE.777)THEN
         EH2(I)=999.
      ELSE
         EH2(I)=Rn(I)-G(I)-H2(I)
      END IF

      IF(H3(I).GE.777)THEN
         EH3(I)=999.
      ELSE
         EH3(I)=Rn(I)-G(I)-H3(I)
      END IF

      IF((DATE(I).GE.831741400).AND.(DATE(I).LE.831811240)) GO TO 300
      IF((DATE(I).GE.831941100).AND.(DATE(I).LE.832011220)) GO TO 300


      IF(H5(I).GE.777)THEN
         EH5(I)=999.
      ELSE
         EH5(I)=Rn(I)-G(I)-H5(I)
      END IF

      IF(H6(I).GE.777)THEN
         EH6(I)=999.
      ELSE
         EH6(I)=Rn(I)-G(I)-H6(I)
      END IF

      IF(H7(I).GE.777)THEN
         EH7(I)=999.
      ELSE
         EH7(I)=Rn(I)-G(I)-H7(I)
      END IF

      GO TO 400

  200 EH1(I)=999.
      EH2(I)=999.
      EH3(I)=999.
      EH5(I)=999.
```

```
      EH6(I)=999.
      EH7(I)=999.

      GO TO 400

 300  EH5(I)=888.
      EH6(I)=888.
      EH7(I)=888.

 400  IF(CT.EQ.3)WRITE(2,1200)
1200  FORMAT(/,3X,'DATE',6X,'RAIN',4X,'Rn',3X,'G',3X,'WD',
     £4X,'U*1',4X,'U*2',4X,'U*3',4X,'U*5',4X,'U*6',4X,'U*7'/
     £7X,'DL1',5X,'E1',5X,'E2',5X,'E3',8X,'H1',5X,'H2',5X,'H3',5X,
     £'H5',5X,'H6',5X,'H7'/6X,'BETA1',4X,'EB1',4X,'EB2',4X,'EB3',
     £7X,'EH1',4X,'EH2',4X,'EH3',4X,'EH5',4X,'EH6',4X,'EH7',//)

      WRITE(2,1300)DATE(I),RAIN(I),Rn(I),G(I),WD(I),UST1(I),UST2(I),
     £UST3(I),UST5(I),UST6(I),UST7(I),DL1(I),E1(I),E2(I),E3(I),
     £H1(I),H2(I),H3(I),H5(I),H6(I),H7(I),BETA1(I),EB1(I),EB2(I),
     £EB3(I),EH1(I),EH2(I),EH3(I),EH5(I),EH6(I),EH7(I)

 1300 FORMAT(I10,2X,F6.2,2X,I4,2X,I4,2X,I4,2X,F5.2,2X,F5.2,2X,F5.2,2X
     £,F5.2,2X,F5.2,2X,F5.2/4X,F8.1,2X,F5.0,2X,F5.0,2X,F5.0,5X,F5.0
     £,2X,F5.0,2X,F5.0,2X,F5.0,2X,F5.0,2X,F5.0/
     £5X,F7.1,2X,F5.0,2X,F5.0,2X,F5.0,5X,F5.0,2X,F5.0,2X,F5.0,2X,F5.0,
     £2X,F5.0,2X,F5.0)

 10   CONTINUE
 5    CONTINUE

      STOP

      END
```

A.3.Text of the program POTEVA.FOR

```
      PROGRAM POTEVA

C     This program is calculating the daily values of the potential
C     evapotranspiration,by the methods of Penman,Thom and Oliver,
C     Priestley and Taylor and Makkink;the daily values of actual
C     evapotranspiration by the advection-aridity approach.

      REAL D3(31),NR(31),SHF(31),WV(31),SWRI(31),DE(31)
      INTEGER DAY(31)

      REAL ETPE(31),ETTO(31),ETPT(31),ETM1(31),ETM2(31)
      REAL ETA1(31),ETA2(31),ETA3(31)

      REAL RA(31),RC,N(31),M
      REAL S(31),GAMMA

      CHARACTER*9 MN(14)
      CHARACTER*14 MONTH(14)
      INTEGER LEN(14)

      DATA LEN/31,30,31,31,30,31,30,31,31,30,31,31,30,31/
      DATA MN/'MAY83.DAT','JUN83.DAT','JUL83.DAT','AUG83.DAT',
     £'SEP83.DAT','OCT83.DAT','NOV83.DAT','DEC83.DAT','MAY84.DAT',
     £'JUN84.DAT','JUL84.DAT','AUG84.DAT','SEP84.DAT','OCT84.DAT'/
      DATA MONTH/'   MAY 1983   ','  JUNE 1983   ','  JULY 1983   ',
     £' AUGUST 1984  ','SEPTEMBER 1983',' OCTOBER 1983 ',
     £'NOVEMBER 1983 ','DECEMBER 1983 ','   MAI 1984   ',
     £'  JUNE 1984   ','  JULY 1984   ',' AUGUST 1984  ',
     £'SEPTEMBER 1984','OCTOBER 1984 '/


C     DEFINITIONS:
C
C         -S:CHANGE OF SATURATED VAPOUR PRESSURE OF AIR(MBAR/K)
C         -GAMMA:PSYCHROMETRIC CONSTANT:0.66 AT ABOUT 295 K(MBAR/K)
C         -D3:DRY-BULB TEMPERATURE AT 3.15M HEIGHT(K)
C         -NR:MEAN DAILY VALUE OF THE NET RADIATION(W/M2)
C         -SHF:MEAN DAILY VALUE OF SOIL HEAT FLUX(W/M2)
C         -WV:MEAN DAILY VALUE OF THE WIND VELOCITY AT 2.14M HEIGHT(M/S)
C         -DE:MEAN DAILY VALUE OF THE WATER VAPOUR DEFICIT IN THE AIR AT
C              ABOUT 2M HEIGHT(MBAR)
C         -RC:CANOPY RESISTANCE(SEC/M)
C         -RA:AERODYNAMIC RESISTANCE(SEC/M)
C         -N:RC/RA
C         -M:RATIO OF THE AERODYNAMIC RESISTANCE OF WATER AS EXPRESSED BY

C            THE PENMAN EQUATION TO THE AERODYNAMIC RESISTANCE OVER A
C            GRASS SURFACE
C            HERE,M=1.9
C         -RS:MEAN DAILY VALUE OF THE SHORT WAVE RADIATION (W/M2)
C
C         -ETPE:POTENTIAL EVAPOTRANSPIRATION FROM PENMAN'S METHOD
C         -ETTO:              _                   THOM AND OLIVER
```

```
C          -ETPT:                   _                   PRIESTLEY AND TAYLOR
C          -ETM1:                   _                   MAKKINK,STANDARD FORM.
C          -ETM2:                   _                   MAKKINK,SECOND FORM.
C          -ETA*:                   _                   THE ADVECTION ARIDITY
C                METHOD
C                1:FROM ETPT AND ETPE
C                2:FROM ETM1 AND ETPE
C                3:FROM ETPT AND ETTO

      DO 5 K=1,14

      OPEN(1,FILE='D:\MEAN24\'//MN(K),STATUS='OLD')
      OPEN(2,FILE='D:\EVAPOT\'//MN(K),STATUS='NEW')

      WRITE(2,2000)MONTH(K)
 2000 FORMAT(6X,'POTENTIAL EVAPOTRANSPIRATION OF THE MONTH OF '
     £,A9,' 1983'
     £/9X,'-ETPE:FROM PENMAN'/9X,'-ETTO:FROM THOM AND OLIVER'/
     £9X,'-ETPT:FROM PRIESTLEY AND TAYLOR'/9X,'-ETM:FROM MAKKINK'/
     £9X, '-ETA:FROM THE ADVECTION-ARIDITY METHOD'/
     £9X,'-NR:NET RADIATION'//
     £2X,'DAY',7X,'ETPE',4X,'ETTO',4X,'ETPT',4X,'ETM1',4X,'ETM2',4X,
     £'ETA1',4X,'ETA2',4X,'ETA3',4X,'NR',//)


      RC=65.
      M=1.9
      GAMMA=0.66

      DO 10 I=1,LEN(K)

      READ(1,1000) DAY(I),D3(I),WV(I),NR(I),SHF(I),SWRI(I),DE(I)
 1000 FORMAT(I6,5F7.1,F8.2)

      IF(D3(I).NE.999.9) D3(I)=D3(I)*0.1

      IF(WV(I).NE.999.9) WV(I)=WV(I)*0.01

C     CALCULATION OF S:

      AS=0.333
      AT=0.01065
      AU=0.0001873
      AV=0.00000322

      IF(D3(I).NE.999.9)THEN
         S(I)=1.333*(AS+2*AT*D3(I)+3*AU*D3(I)**2+4*AV*D3(ID)**3)
      ELSE
         S(I)=999.99
      ENDIF

C     CALCULATION OF RA:

      RA(I)=(4.72*(ALOG(2.14/0.01))**2)/(1+0.54*WV(I))
```

```
C     CALCULATION OF N:

      N(I)=RC/RA(I)


C     PENMAN'S METHOD:
C     ****************

      ETPE(I)=(S(I)/(S(I)+GAMMA))*(NR(I)-SHF(I))+
     &(GAMMA/(S(I)+GAMMA))*(3.7+4*WV(I))*DE(I)

      IF(S(I).EQ.999.99) ETPE(I)=999.99
      IF(NR(I).EQ.999.9) ETPE(I)=999.99
      IF(SHF(I).EQ.999.9) ETPE(I)=999.99
      IF(WV(I).EQ.999.9) ETPE(I)=999.99
      IF(DE(I).EQ.999.99) ETPE(I)=999.99

C     THOM AND OLIVER'S METHOD:
C     *************************

      ETTO(I)=(S(I)/(S(I)+GAMMA*(1+N(I))))*(NR(I)-SHF(I))+
     &(M*GAMMA/(S(I)+GAMMA*(1+N(I))))*(7.4+4*WV(I))*DE(I)

      IF(S(I).EQ.999.99) ETTO(I)=999.99
      IF(NR(I).EQ.999.9) ETTO(I)=999.99
      IF(SHF(I).EQ.999.9) ETTO(I)=999.99
      IF(WV(I).EQ.999.9) ETTO(I)=999.99
      IF(DE(I).EQ.999.99) ETTO(I)=999.99

C     PRIESTLEY AND TAYLOR:
C     *********************

      IF(DAY(I).GT.83273) THEN
         ETPT(I)=999.99
      ELSE
         ETPT(I)=1.28*(S(I)/(S(I)+GAMMA))*(NR(I)-SHF(I))
      ENDIF

      IF(S(I).EQ.999.99) ETPT(I)=999.99
      IF(NR(I).EQ.999.9) ETPT(I)=999.99
      IF(SHF(I).EQ.999.9) ETPT(I)=999.99

C     MAKKINK:
C     ********

      ETM1(I)=0.65*(S(I)/(S(I)+GAMMA))*SWRI(I)

      ETM2(I)=0.65*(S(I)/(S(I)+GAMMA))*(SWRI(I)-2*SHF(I))

      IF(S(I).EQ.999.99) ETM1(I)=999.99
      IF(S(I).EQ.999.99) ETM2(I)=999.99
      IF(SWRI(I).EQ.999.9) ETM1(I)=999.99
      IF(SWRI(I).EQ.999.9) ETM2(I)=999.99
```

```
      IF(SHF(I).EQ.999.9) ETM2(I)=999.99

C     ADVECTION-ARIDITY METHOD:
C     *************************

      IF(DAY(I).GT.83243) THEN
         ETA1(I)=999.99
         ETA2(I)=999.99
         ETA3(I)=999.99
      ELSE
         ETA1(I)=2*ETPT(I)-ETPE(I)
         ETA2(I)=2*ETM1(I)-ETPE(I)
         ETA3(I)=2*ETPT(I)-ETTO(I)
      ENDIF

      IF(ETPT(I).EQ.999.99) ETA1(I)=999.99
      IF(ETPE(I).EQ.999.99) ETA1(I)=999.99
      IF(ETM1(I).EQ.999.99) ETA2(I)=999.99
      IF(ETPE(I).EQ.999.99) ETA2(I)=999.99
      IF(ETPT(I).EQ.999.99) ETA3(I)=999.99
      IF(ETTO(I).EQ.999.99) ETA3(I)=999.99


       WRITE(2,2100)DAY(I),ETPE(I),ETTO(I),ETPT(I),ETM1(I),ETM2(I)
     £,ETA1(I),ETA2(I),ETA3(I),NR(I)
 2100 FORMAT(I6,1X,8F8.2,F6.1)

 10   CONTINUE

 5    CONTINUE

      STOP
      END
```

A.4.Text of the program ANALYETP.FOR:

```
      PROGRAM ANALYETP

C     In this program,the relationships between the values of
C     potential evapotranspiration found by different methods are
C     analysed.
C     The best straight line and the correlation coefficient are
C     calculated.

      REAL ETPE(670),ETTO(670),ETPT(670),ETM1(670),ETM2(670)
      REAL ETA1(670),ETA2(670),ETA3(670)
      INTEGER NR(670)
      INTEGER DAY(670)
      INTEGER N1,N2,N3,N4
      REAL C1,C2,C3,C4
      REAL D1,D2,D3,D4
      REAL E1,E2,E3,E4
      REAL F1,F2,F3,F4
      REAL P1,P2,P3,P4
      REAL L1,L2,L3,L4
      REAL M1,M2,M3,M4
      REAL A1,A2,A3,A4
      REAL B1,B2,B3,B4
      REAL RHO1,RHO2,RHO3,RHO4

      OPEN(1,FILE='D:\MEAN24\ETP83.DAT',STATUS='OLD')
      OPEN(2,FILE='D:\MEAN24\ANALYETP.RES',STATUS='NEW')

C     SETTING THE SUMS TO 0

      C1=0
      D1=0
      E1=0
      F1=0
      P1=0
      N1=0

      C2=0
      D2=0
```

```
      E2=0
      F2=0
      P2=0
      N2=0

      C3=0
      D3=0
      E3=0
      F3=0
      P3=0
      N3=0

      C4=0
      D4=0
      E4=0
      F4=0
      P4=0
      N4=0


      READ(1,1000)
1000  FORMAT(///////////////)

      DO 10 I=1,670

      READ(1,1100)DAY(I),ETPE(I),ETTO(I),ETPT(I),ETM1(I),ETM2(I),
     &ETA1(I),ETA2(I),ETA3(I)


1100  FORMAT(I6,1X,8F8.2)


      CALL SUM(ETTO(I),ETPE(I),C1,D1,E1,F1,P1,N1)
      CALL SUM(ETTO(I),ETPT(I),C2,D2,E2,F2,P2,N2)
      CALL SUM(ETTO(I),ETM1(I),C3,D3,E3,F3,P3,N3)
      CALL SUM(ETTO(I),ETM2(I),C4,D4,E4,F4,P4,N4)

10    CONTINUE


      CALL CORREL('ETTO','ETPE',A1,B1,C1,D1,E1,F1,L1,M1,P1,RHO1,N1)
      CALL CORREL('ETTO','ETPT',A2,B2,C2,D2,E2,F2,L2,M2,P2,RHO2,N2)
      CALL CORREL('ETTO','ETM1',A3,B3,C3,D3,E3,F3,L3,M3,P3,RHO3,N3)
      CALL CORREL('ETTO','ETM2',A4,B4,C4,D4,E4,F4,L4,M4,P4,RHO4,N4)
```

```
      STOP
      END


      SUBROUTINE SUM(X,Y,C,D,E,F,P,N)

      REAL X,Y
      REAL C,D,E,F,P
      INTEGER N

      IF(X.EQ.999.99)GO TO 200
      IF(Y.EQ.999.99)GO TO 200
      C=C+X
      D=D+Y
      E=E+X**2
      F=F+Y**2
      P=P+X*Y
      N=N+1
      GO TO 210

 200  C=C
      D=D
      E=E
      F=F
      P=P
      N=N

 210  RETURN

      END


      SUBROUTINE CORREL(V1,V2,A,B,C,D,E,F,L,M,P,RHO,N)

      REAL A,B,C,D,E,F,L,M,P,RHO
      INTEGER N
      CHARACTER*4 V1,V2

C     CALCULATION OF THE COEFFICIENTS OF THE LINEAR REGRESSION
C     BETWEEN TWO VARIABLES

C     THE EQUATION OF THE LINE OF REGRESSION IS : Y=A*X+B

C     C:SUM OF THE VALUES OF X
C     D:SUM OF THE VALUES OF Y
C     E:SUM OF THE SQUARED VALUES OF X
```