Int. Agrophysics, 2001, 15, 37-49

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

Comparison of daily evapotranspiration rates obtained from water balance model and modified Bowen's ratio method**

J. Olejnik[1], F. Eulenstein[2], A. Kędziora[3], and A. Werner[2]*

[1]ADAU, Agrometeorology Department, Agricultural University of Poznań, Witosa 45, 60-667 Poznań, Poland
[2]ZALF, Center for Agricultural Landscapes and Land Use Research, Müncheberg, Germany
[3]RCAFE, Research Centre for Agricultural and Forest Environment, Polish Academy of Sciences, Bukowska 19
60-809 Poznań, Poland

Received October 11, 1999; accepted January 12, 2000

A b s t r a c t. The processes of energy and water exchange between the earth surface and atmosphere have a very significant influence on the microclimatic conditions and consequently, on plant production. Evapotranspiration is one of the most important processes that connect energy and water balance of a cultivated field with plant growth. This paper compares the results of simulations and measurements of evapotranspiration from the cultivated fields in Middle Europe. The modelling system THESEUS was used in this study. Evapotranspiration was also calculated from the latent heat flux density (LE) measured by the use of a modified Bowen's ratio method. The models, as well as the modification of the Bowen's ratio procedure are described. Heat balance components for 8 measuring sessions (81 days) were used in the comparison. There was a good agreement between model simulations and measurements. The average relative error in the evapotranspiration estimation by the model was about 5% for one month or longer integration period.

K e y w o r d s: evapotranspiration, modelling, Bowen's ratio method

INTRODUCTION

Within a landscape, the ability to transform and displace heat and water is of crucial importance for the landscape functioning, including natural resources conservation and sustainable development of agriculture. This ability is limited to the most important processes that occur in the earth-atmosphere system, i.e., exchange of energy and water in the boundary layer. These processes are crucial for the creation of climatic conditions on a global scale, as well as on a local or microscale, and have a vital impact on plant production. On the other hand, plant cover, land-use structure and habitat moisture influence the rate and character of these processes, which means they determine the proportions of energy and water vapour fluxes exchanged.

In Western Poland and Eastern Germany, large lowlands of the Elbe and Oder catchments are mainly used for agriculture. Current and the future agricultural economic conditions will cause various changes in the land-use structure and plant cover. There is a need to evaluate the method, which allows us to determine the impact of these changes on the exchange of heat and water between the land and atmosphere. In addition to this, land-use strategies providing sustainable agriculture and protection of the water resources require information on the factors controlling the water and heat balance.

Water, which reaches the Earth surface partly, returns to the atmosphere due to the evapotranspiration process and partly goes to the sea as a runoff. The available energy and soil moisture are the most important physical factors which limit the amount of evapotranspiration. On the other hand, the species of plants, which cover the earth surface, as well as their development stage, are the most important biological factors. So, models that simulate water balance, independently of simulation scale, should include parameterization of both physical and biological processes, which occur in the environment.

Numerous papers on the modelling of heat and water balance components in different scales have been published in recent years, i.e., Thom and Oliver, 1977; Holtslag and Van Ulden, 1983; Morton, 1983; McNaughton and Spriggs, 1985; Sellers and Dorman, 1986; Kovacs, 1988; Holtslag and De Bruin, 1988; Olejnik, 1988a,b; Van de Griend and

*Corresponding author e-mail: kedan@poczta.onet.pl
**This work was partly supported by the State Committee for Scientific Research, Poland under grant No. 6P04F01915.

Van Boxel, 1989; Olejnik and Kędziora, 1991; Beljaars and Holtslag, 1991; Olejnik, 1996; Wegehenkel, 1997a . These models can be applied at different scales: from a field to a regional scale, but with an increase in the scale, some important problems occur (i.e., availability of input data such as soil moisture for large areas). One of the most important problems during the procedure of water balance modelling, is coupling atmospheric and land surface processes. A characteristic length of atmospheric processes is said to be 100 km (Kundzewicz, 1990), while the characteristic length of surface processes is smaller by many orders of magnitude (down to the cellular scale for many biological processes). Land surface processes are too small, too fast, too numerous and too heterogeneous to be represented explicitly in models, and therefore the parameterization of these processes is necessary.

It can be stated that the THESEUS model for water balance estimation (at the field or regional scale) created at the ZALF (Wegehenkel, 1997a; 1999), is a good example of a pertinent selection of parameterization of physical and biological processes which significantly influence the water balance of the agricultural landscape. Using this model, it is possible to estimate the evapotranspiration of a chosen agricultural field (or landscape) with a one day time step. To evaluate the results obtained by the THESEUS model, measurements of evapotranspiration were taken in some selected fields in the eastern part of Germany and the western part of Poland. To estimate evapotranspiration, heat balance components of the selected fields were measured and calculated. The modified Bowen's ratio method was used.

The heat balance equation can be written as follows:

$$R_n + LE + S + G = 0 \tag{1}$$

where R_n is a net radiation flux density, LE is latent heat flux density (L is the heat of water vaporisation and E is the evapotranspiration), S is a sensible heat flux density and G is the soil heat flux density.

After determination of all four components of heat balance equation (Eq. (1)), evapotranspiration can be calculated by the transformation of Eq. (1):

$$E = -\left(R_n + S + G\right) / L . \tag{2}$$

The values of evapotranspiration obtained by the measurements were then compared with evapotranspiration simulated by THESEUS.

INVESTIGATION SITES

In this paper the results of 8 measurement sessions carried out in Poland and Germany are presented. The measurements were carried out in the neighbourhood of Müncheberg, District of Brandenburg, East Germany, and Turew, the region of Wielkopolska, West Poland, (Table 1). In Turew and Müncheberg, climate is transitional (between continental and marine), with moderate temperatures (8.3 ^{o}C - annual average) and air humidity (78 and 81% in Turew and in Müncheberg, respectively), low measured precipitation (annually 530 mm in both sites). Relative sunshine is moderate in summers (42 and 45% in Turew and Müncheberg, respectively) and low in winters (18 and 19%). Global radiation differs a little between these two sites, reaching in Turew 3600 MJ m^{-2}, and in Müncheberg - 3700 MJ m^{-2} in a year, while net radiation is nearly the same (about 1470 MJ m^{-2}) at both sites (Table 2).

Soils in Turew and Müncheberg are mainly light to moderate textured sandy loam and loamy soils that belong to the Mollisols-Aquolls-loamy mixed, mesic or Alfisols-sandy to loamy mixed, mesic with moderate organic matter concentration. Ground water level ranges from 0.5 m to a few meters below the ground surface with low (sandy soil) to moderate water retention. Intensive agriculture and many forests create a mosaic landscape.

METHODS OF MODELING AND MEASUREMENTS

The THESEUS model

The modelling system THESEUS (Toolbox for Hydro-Ecological Simulation and Evaluation Utilities) from Wegehenkel (1997a, 1999) was used in this study. This modelling system consists of different sub-models for atmosphere, plant and soil, which can be combined to build an appropriate simulation model for a wide range of purposes and data bases in the context of water balance and crop production modelling. An overview of all the available moduli in the THESEUS is given in Table 3.

In our investigations, the following moduli were used (Table 3): (i) calculation of ETP according to Wendling *et al.* (1991) formula, (ii) determination of transpiration, evapotranspiration and interception based on the semiempirical plant model according to Koitzsch and Günther (1990), and (iii) determination of soil water balance by the use of a multiple-layer model combined with a non-linear storage routing technique according to Glugla (1969) and Wegehenkel (1997b).

T a b l e 1. Geographical information about the investigation sites

Site	Country	Latitud	Longitude	Elevation	Vegetation season
Turew (Tur.)	Poland	52°30' N	17°00' E	80 m	IV. - X
Müncheberg (Mun.)	Germany	52°35' N	14°10' E	80 m	IV. - X

T a b l e 2. Climatological characteristics of the investigation sites (1931-1960 period). *T* - air temperature (°C), *f* - relative air humidity (%), *e* - water vapor pressure (hPa), *P* - precipitation (mm), *u* - wind speed (m s^{-1}), *n* - sunshine duration (h), *rs* - relative sunshine (%), *Rs* - global solar radiation (MJ m^{-2}), *Rn* - net radiation (MJ m^{-2})

Place	Season	Seasonal values of meteorological parameters								
		T	*f*	*e*	*P*	*n*	*n*	*rs*	*Rs*	*Rn*
Tur.	Spring	8.0	74	8.0	125	2.8	493	38	1173	489
	Summer	17.6	70	14.6	197	2.4	607	42	1553	846
	Autumn	8.5	83	9.7	115	2.4	342	31	630	169
	Winter	-1.0	87	5.2	92	2.9	140	18	264	-39
	Year	8.3	78	9.4	529	2.6	1582	32	3620	1465
Mun.	Spring	7.5	76	7.9	113	3.2	524	40	1201	496
	Summer	17.1	75	14.1	183	2.8	658	45	1607	861
	Autumn	8.7	85	9.8	128	3.1	320	32	627	166
	Winter	-0.5	87	5.5	103	3.5	152	19	272	-44
	Year	8.2	81	9.3	527	3.1	1654	34	3707	1479

Tur. - Turew, Mun.- Müncheberg

T a b l e 3. Components of the THESEUS model (Wegehenkel 1999) (***) – moduli used in the modelling procedure described in this paper

Model section and its output	Model equation	Input data requirements
	Atmosphere section	
ETP	acc. to Haude (1955)	*D, k*
ETP	acc. to Turc (1961)	*Rn, T*
ETP	acc. to Penman (1948)	*Rn, T, D, u*
ETP ***	acc. to Wendling et al. (1991)	*Rn, T, D, u*
ETP	acc. to Penman-Monteith (Monteith and Unswotrh 1990)	*Rn, T, D, u*
	Plant models section	
ETR	specific crop type correction coefficient (*ETP*/*ETR*)	crop type
	acc. To Sponagel (1980)	crop type, *T*
		crop type, *T*, plant data
Plth, Rt, Sdg, INT, TR, ETR ***	plant model acc. to Koitzsch and Gunter (1990) in combination with sum of effective temperature	
Plth, Rt, Sdg, INT, TR, ETR, LAI, Biom	plant model acc. to Stenitzer (1988) in combination with Penman-Monteith approach	
	Soil water dynamics section	
EVP, Perc, next day *θ*	one layer (dimension) plate-theory model acc. to Renger *et al.* (1974)	Initial values of: *P, θ, FC,PWP*,
EVP, Perc, next day *θ* ***	plate-theory model in combination with nonlinear storage routing - Glugla (1969), Wegehenkel (1997b)	Initial values of: *P, θ, FC,PWP*
EVP, Perc, Inf, CAP,I, next day *θ*	Darcy-modell SAWAH (Ten Berge *et al.* 1995)	Initial values of: *P, θ, pF, K*

Symbols:
Biom - biomass (kg ha^{-1})
CAP- capillary rise (mm d^{-1})
D - saturation water vapour pressure deficit (g cm^{-3})
ETP - potential evapotranspiration (mm d^{-1})
ETR - actual evapotranspiration (mm d^{-1})
EVP - actual evaporation (mm d^{-1})
FC - field capacity (Vol%, mm dm^{-1})
PF - soil water retention function
I - infiltration (mm d^{-1})
INT - interception (mm d^{-1})
K - soil hydraulic conductivity (mm d^{-1})
k - plant specific coefficient
LAI - leaf area index (m^2 m^{-2})
P - precipitation (mm)
Perc - percolation (mm d^{-1})
Plth - plant height (cm)
PWP - permanent wilting point (%Vol)
Rn - net radiation (J cm^{-2})
Rt - rooting depth (cm)
Sdg - soil covering degree (%)
T - daily average air temperature (°C)
TR - actual transpiration (mm d^{-1}),
u - wind speed (m s^{-1})
θ - soil water content (% Vol)

In the multi-layer model, soil profile is divided into layers with 10 cm thickness down to a depth of 150 cm. The texture classes were determined in the field. The required input parameters for the soil water moduli such as water content at field capacity and at wilting point are derived automatically within the modelling system THESEUS from the soil texture class of the corresponding soil layer modified by organic mater content, hydromorphic patterns and bulk density class.

Time resolution of the THESEUS model is one day, and therefore it needs inputs of standard meteorological data with the same time resolution (air temperature, precipitation etc). A large graphic package is attached to the THESEUS model. It controls courses of the modelled or measured parameters in a very convenient way. Figure 1a shows courses of precipitation (*P*), soil moisture of the upper soil layer (Θ) and *ETR* modelled by THESEUS for a sunflower field, starting from 1 January 1995 to 30 June 1995 that is from the beginning of the year to the 180th day of the year (DOY). During this period, the measuring session was carried out from 8 June 1995 to 14 June 1995 (that is from 159 to 165 DOY). In Fig.1b, THESEUS simulated values of *ETR*(*T*) were compared with *ETR*(*B*) obtained by the use of a modified Bowen's ratio method (see pages 42 and 43). In the beginning of every measuring session, the measurement of soil moisture and plant height were carried out (to measure soil moisture, a TDR technique was chosen). The results of these measurements were then compared with the values obtained by the model. Sometimes the simulated soil moisture and plant height were slightly different in comparison to the measured data, and therefore starting from the first day of the Bowen's ratio measurements, soil moisture and plant height were corrected in the model input data set according to the measurements. Next, the simulation procedure was started again. In Fig.1b the results of such a procedure is shown (*ETR*(*T*)-*cor*.). The bold line (or white bars) represents the *ETR*(*T*) (evapotranspiration simulated by the THESEUS without correction of soil moisture and plant height), the medium line (or grey bars) represents the corrected modelled evapotraspiration *ETR*(*T*)-*cor*. The correction procedure was applied for all the measuring sessions and therefore in following chapters the symbol of simulated corrected evapotranspiration values (*ETR*(*T*)-*cor*.) was abbreviated to *ETR*(*T*).

The same method was used for all 8 periods of evapotranspitarion modelling by the THESEUS model.

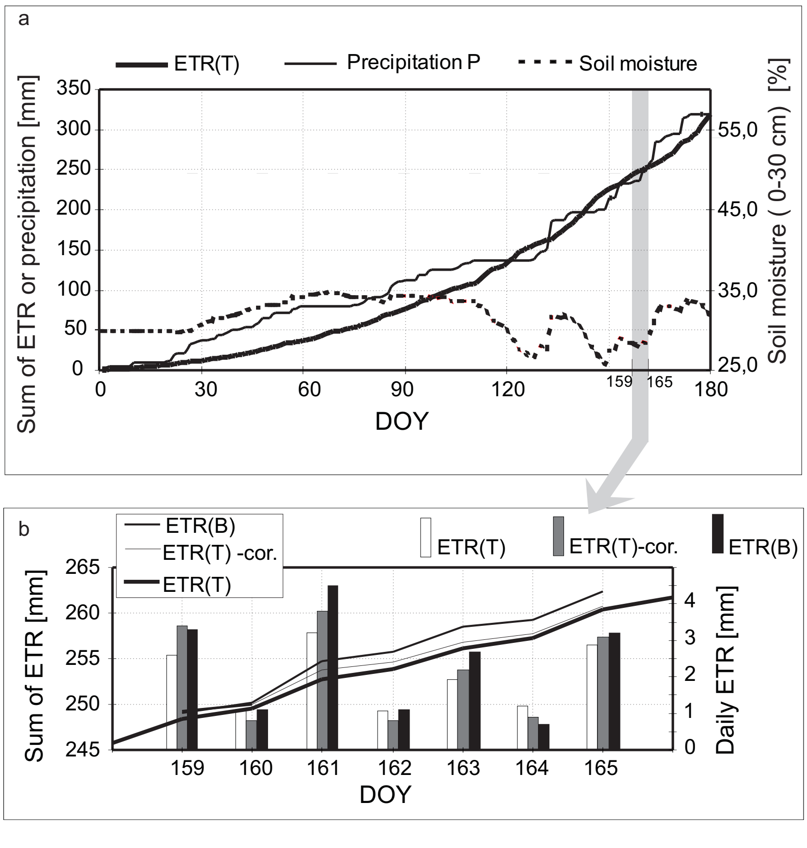

Fig. 1. Results of the THESEUS model application to a sunflower field in 1995: a) courses of simulated (evapotranspiration and soil moisture) and measured (precipitation) parameters, b) comparison of evapotranspiration measured (*ETR*(*B*)) and simulated (*ETR*(*T*)) as well as the simulated corrected (*ETR*(*T*)-*cor*.).

Soil moisture measurements

In order to validate simulations, it was necessary to have an easy access to a large number (places and measuring-dates) of measurements for the soil water content from the study sites. Time domain reflectometry (TDR) is a non-destructive method for measuring soil-water content. This method was developed by Topp *et al*. (1980). It integrates the volumetric water content of a soil profile along the length of a pair of metal rods (antennas) that must be driven into the ground. The size of the sample area (sphere) depends on the length and the distance between the rods (Ferré *et al*., 1998). The method produces reliable and comparable results to gravimetric measurements (Jenkins, 1989; Topp and Davis, 1985) in soils low in clay content and electrolytes as in this study.

Measurements of heat balance components

Description of the measuring system

In the Department of Agrometeorology, Agricultural University of Poznań, investigations on the heat and water balance components have been carried out for many years, Olejnik (1996). A mobile measurement system has been used for many research expeditions in numerous places in Asia and Europe. The complete measuring system is shown in Fig. 2. To measure radiation fluxes, a CNR-1 sensor is used. The CNR-1 consists of pyranometers facing upwards and downwards (PA) and upwards and downwards facing pyrradiometers (PR), which are used to measure incoming and outgoing short- and long-wave radiation fluxes, respectively.

Soil heat fluxes were measured using commercial soil heat flux plates (SHP, Fig. 2). Ten plates (SHP) were placed at the depth of about 0.03 m.

Psychrometers were used (Fig. 2 - PSM) to measure the profiles of air temperature and water vapour pressure using quartz crystal thermometers (Olejnik, 1988b). Oscillation frequency (28 MHz) of the quartz crystal depends only on temperature and can be measured over a long distance of the signal wire.

Additionally, five optical cup anemometers (Fig. 2 - CA) are installed at different heights together with a wind-direction sensor.

Electrical signals from all the sensors are measured by a milivoltmetre (mV) or frequencymeter (FM) installed inside a data logger (DL) via channel selectors (CS1, CS2 or CS3).

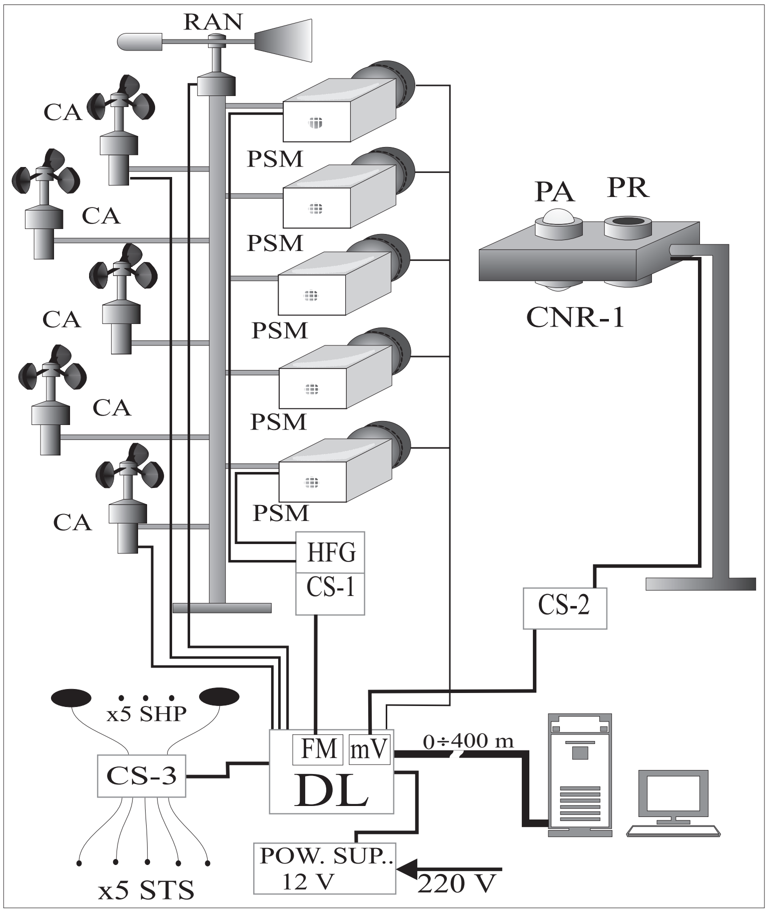

Fig. 2. System for measuring heat balance components measurements using the modified Bowen's ratio method.

The data logger is also responsible for channel selectors control and during the measurement procedure all data is stored in the data logger memory. The end task of the data logger is to control ventilation system of the psychrometers. Five commercial aspirators are used; they start to work three minutes before the measuring cycle begins.

All the measuring conditions (time of data collection, numbers of sensors etc.) can be changed by the operator using the main computer (PC). A standard measuring cycle consists of: 40 series of dry- and wet-bulb temperature measurements, 40 series short- and long-wave radiation measurements, 40 series of soil heat measurements and 2 series of wind speed (at the beginning and at the end of one measurement cycle). One measuring cycle takes about 20 min, and in the standard mode, is repeated every hour of the day (24 times). After the measuring procedure, the collected data is stored on the PC hard disk. The whole system needs a 12V-power supply.

Description of the calculation methods

The Bowen's ratio is defined as follows:

$$\beta = S / LE. \tag{3}$$

Using Eqs (1) and (2), it is possible to calculate latent and sensible flux density levels using the so called Bowen's ratio method:

$$LE = -(R_n + G) / (1 + \beta) \tag{4}$$

$$S = -(R_n + G) / (1 + 1/\beta). \tag{5}$$

It is known that latent (*LE*) and sensible (*S*) heat flux density levels are proportional to wind speed gradients, as well as water vapour and air temperature gradients, respectively (Monteith, 1975). The following relationship can be used for these flux level estimations:

$$LE \sim \frac{\partial e}{\partial z}\frac{\partial u}{\partial z} \tag{6}$$

$$S \sim \gamma \frac{\partial T}{\partial z}\frac{\partial u}{\partial z} \tag{7}$$

where γ is psychrometric constant, e - water vapour pressure, T - air temperature, z - hight above ground level, and u - wind speed.

Using Eqs (6), (7), and (3) the Bowen's ratio can be written as follows:

$$\beta = \gamma \frac{\partial T}{\partial z} / \frac{\partial e}{\partial z}. \tag{8}$$

In the measuring practice, gradients in the Eq. (8) are replaced by differential quotients (Monteith, 1975; Black, 1971):

$$\frac{\partial e}{\partial z} \approx (e_2 - e_1) / (z_2 - z_1) \tag{9}$$

$$\frac{\partial T}{\partial z} \approx (T_2 - T_1) / (z_2 - z_1) \tag{10}$$

where: e_1 and e_2 are water vapour pressure measured at two levels 1 and 2, T_1 and T_2 are air temperature measured at two levels 1 and 2, $z_1$and z_2 are height above the ground of the two measuring levels 1 and 2.

After calculating the Bowen's ratio (Eqs (8)-(10)), it is possible to estimate latent and sensible heat fluxes using Eqs (4) and (5) (of course, simultaneously, the measurements of R_n and G are necessary).

The Bowen's ratio method of *LE* and *S* estimation described above is commonly used by many investigators (Spittlehouse and Black; 1981) and there are even commercial measuring units, based on this method. Unfortunately, using only two measuring levels, is possibile to make errors when measurements are carried out in a patchy landscape. Temperature and water vapour sensors must be located within an internal boundary layer characteristic of the ecosystem under investigation (fetch). The only way to meet the fetch requirements, using only two layers of measurement, is to carry out measurements of latent and sensible heat fluxes for relatively large fields. In the Central Europe, landscape is often very patchy and it is hard to meet the fetch requirements. Therefore, Olejnik (1996) proposed a modification of Bowen's ratio method. Air temperature and water vapour data is collected from five measuring levels (instead of two as in the original Bowen's ratio method). With the data on air temperature at five levels, it is possible to estimate temperature (T_z) as a function of height (the same can be done for water vapour pressure, e_z). Using measurements at five levels and statistical methods these functions can be determined as:

$$T_z = f_1(z) \tag{11}$$

$$e_z = f_2(z) \tag{12}$$

where z is height above the ground.

In the Eqs (9) and (10) differential quotients can be replaced by the derivatives of functions described in the Eqs (11) and (12).

Finally, the Bowen's ratio (Eq. (8)) and latent and sensible heat fluxes can be calculated at any height, between the first and the fifth sensor, as follows:

$$\beta_z = \gamma \left(T_z^{'} / e_z^{'}\right) \tag{13}$$

$$LE_z = -(R_n + G) / (1 + \beta_z) \tag{14}$$

$$S_z = -(R_n + G) / (1 + 1/\beta_z). \tag{15}$$

The proposed modification of the Bowen's ratio method requires more sensors but creates an opportunity to calculate latent and sensible heat fluxes at any height between the first and the fifth sensor. It allows for controlling thickness of the stable flux layer and consequently estimating heat balance in a patchy landscape.

Calculation of latent (*LE*) and sensible (*S*) heat fluxes by the use of the modified Bowen's ratio method is shown on the basis of one selected measuring cycle of air temperature and vapour pressure profiles (Fig. 3). Using the psychrometric equation, water vapour data are calculated on the basis of dry and wet bulb temperatures at 5 levels. The result of the calculations for a 40 profile series during one measuring cycle is shown in Fig. 3a. On the basis of these profiles, mean values of air temperature (*T*) and water vapour pressure (*e*) at 5 levels were calculated (Fig. 3b). Using statistical and numerical methods, air temperature and vapour pressure, as functions of height, can be found (Eqs (11) and (12)). Afterwards, calculations of *LE* and *S* can be done (Eqs (13) - (15)). The result of such a procedure is shown in Fig. 3c.

During our joint investigation described in the next chapter, the above procedure was used. After estimation of heat balance components (Eq. (1)), evapotranspiration was calculated by the use of the Eq. (2), and compared to the evapotranspiration as modelled by the THESEUS model.

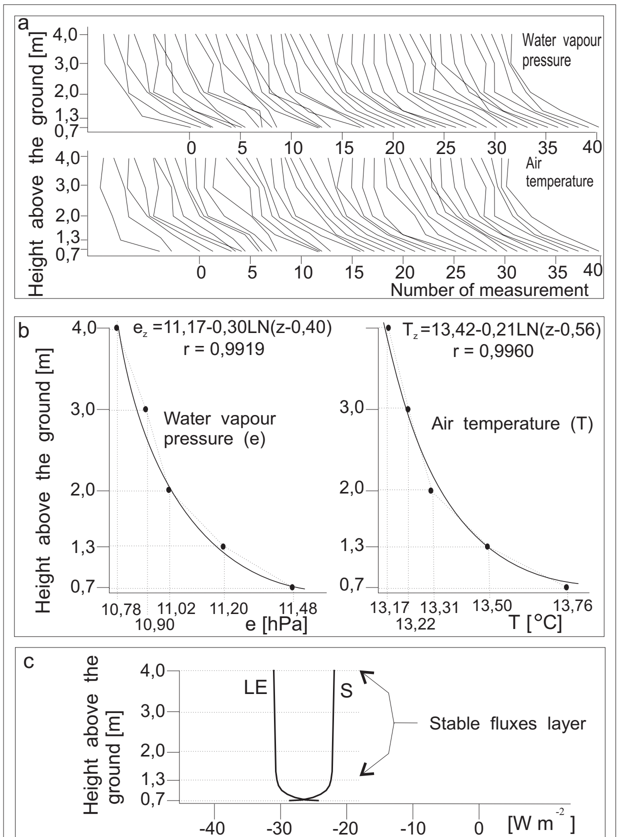

Fig. 3. Results of measuring system for the modified Bowen's ratio method: a) results of measuring air temperature and water vapour pressure profiles, b) statistical approximation of functions e_z and T_z on the basis of measurements and calculations of mean profiles, c) latent (*LE*) and sensible (*S*) heat fluxes estimation as a function of height (*z*).

Measuring periods and types of surfaces

The measurements were carried out during 8 periods in the fields near Turew and Müncheberg. Heat balance components were measured for different plant canopies and for bare soil. In Turew, measurements were taken in alfalfa and sugar-beet crops as well as bare soil, while at Müncheberg, measurements were taken in oat, wheat and sunflower crops. Measurements during sessions 1 to 4 were carried out in Turew and sessions from 5 to 8 in Müncheberg. The length of the measuring periods varied from 7 days (sessions 6, 7 and 8 in Müncheberg) to 16 days (sessions 3 and 4 in Turew). The whole measuring time consisted of 81 days. General information about the measuring period (place, date, crop type) and meteorological data are shown in Table 4.

RESULTS AND DISCUSSION

Heat balance components and evapotranspiration estimated by the Bowen's ratio method (*ETR*(*B*)), as well as simulated by the THESEUS (*ETR*(*T*)) for the same periods are shown in Table 5. In addition, daily averages of meteorological data and heat balance components, as well as evapotranspiration *ETR*(*B*) and *ETR*(*T*) for all 8 measuring sessions are combined in Table 6. Comparison of daily rates of evapotranspiration (mm) calculated from latent heat flux density *ETR*(*B*) and simulated by THESEUS *ETR*(*T*) shows a very good agreement. For all 81 measurement days the sum of *ETR*(*B*) and *ETR*(*T*) was 174.1 and 165.2 mm, respectively (Table 6). The difference of 8.9 mm means that the relative estimation error of evapotranspiration by the THESEUS model is about 5% for 81 days of comparison. The relative estimation error of the daily evapotranspiration rate was calculated using the following formula:

$$REE = \left[ETR(B)_x - ETR(T)_x\right] / ETR(B)_x \qquad (16)$$

where: *REE* is a relative estimation error, *x* is the day number in the individual session or the whole set of data.

For the whole set, the average absolute daily error is equal to 0.1 mm.

In Fig. 4, daily evapotranspiration values estimated by both methods are shown. Linear regression was calculated on the basis of the whole data set. It is easy to see that the THESEUS model underestimates daily evapotranspiration rate (particularly for the evapotranspiration rate greater than 2 mm d^{-1}). The regression equation for the whole set is as follows (correlation r = 0.993):

$$ETR(T) = 0.87\ ERT(B) - 0.19. \qquad (17)$$

T a b l e 4. Meteorological data for 8 measuring sessions S1..S8 (81 days), Tur. - Turew, Mun. - Müncheberg

X	*x*	Meteorological data (daily averages)					
		Rn	*G*	*LE*	*S*	*ETR* (*B*)	*ETR* (*T*)
		(W m^{-2})				(mm day^{-1})	
		S1 Tur. 2-11 September 1995 Alfalfa					
1	1	48	2	-37	-13	1.3	1.6
2	2	30	6	-44	9	1.6	1.2
3	3	61	2	-61	-2	2.2	2.3
4	4	30	6	-31	-4	1.1	0.9
5	5	71	-4	-57	-11	2.0	1.2
6	6	102	-2	-76	-24	2.7	1.8
7	7	28	5	-23	-10	0.8	1.3
8	8	12	5	-17	0	0.6	1.2
9	9	106	-4	-81	-21	2.9	2.6
10	10	109	-4	-83	-21	2.9	2.1
		S2 Tur. 2-11 September 1995 Bare soil					
11	1	51	-3	-28	-20	1.0	0.9
12	2	26	-1	-33	8	1.2	0.6
13	3	56	-5	-39	-11	1.4	1.3
14	4	31	-1	-11	-18	0.4	0.6
15	5	58	-3	-13	-42	0.4	1.2
16	6	85	0	-28	-57	1.0	1.7
17	7	29	0	-12	-17	0.4	0.7
18	8	10	0	-10	6	0.4	0.2
19	9	84	-8	-41	-35	1.4	1.9
20	10	88	-7	-32	-48	1.1	2.1
		S3 Tur. 9-24 September 1997 Bare soil					
21	1	50	-3	-26	-22	0.9	1.2
22	2	82	1	-35	-48	1.2	1.8
23	3	77	4	-40	-40	1.4	1.8
24	4	47	2	-44	-5	1.6	1.2
25	5	30	3	-19	-14	0.7	0.5
26	6	60	3	-50	-12	1.8	1.3
27	7	93	2	-74	-21	2.6	1.8
28	8	63	2	-43	-23	1.5	1.4
29	9	14	3	-15	-2	0.5	0.5
30	10	39	4	-22	-20	0.8	0.8
31	11	61	3	-32	-32	1.1	1.2
32	12	48	2	-27	-23	1.0	1.1
33	13	52	5	-37	-20	1.3	1.1
34	14	56	4	-36	-23	1.3	1.2
35	15	14	5	-11	-8	0.4	0.4
36	16	9	5	-10	-4	0.3	0.2
		S4 Tur. 9-24 September 1997 Sugar beats					
37	1	48	5	-54	0	1.9	1.5
38	2	75	2	-69	-8	2.4	2.4
39	3	62	6	-67	-1	2.4	2.3
40	4	49	3	-56	5	2.0	1.6
41	5	26	4	-25	-5	0.9	1.9
42	6	53	4	-59	2	2.1	1.1
43	7	74	3	-72	-4	2.5	2.3
44	8	53	4	-60	3	2.1	1.8
45	9	15	5	-29	9	1.0	1.3
46	10	35	7	-44	2	1.5	1.0
47	11	54	5	-61	1	2.2	1.7
48	12	47	5	-56	4	2.0	1.6
49	13	47	4	-58	7	2.0	1.4
50	14	52	4	-70	14	2.5	1.8
51	15	15	6	-25	4	0.9	0.6
52	16	8	5	-13	0	0.4	0.2
		S5 Mun. 8-15 June 1994 Oat					
53	1	179	-4	-166	-9	5.9	6.0
54	2	43	13	-65	9	2.3	2.5
55	3	122	5	-114	-14	4.0	3.2
56	4	159	3	-133	-29	4.7	4.5
57	5	232	-1	-203	-28	7.2	6.1
58	6	68	9	-62	-14	2.2	2.1
59	7	160	1	-143	-17	5.0	5.4
60	8	210	5	-179	-36	6.3	6.2
		S6 Mun. 8-14 June 1995 Sunflower					
61	1	118	-1	-94	-23	3.3	3.4
62	2	25	10	-31	-4	1.1	0.8
63	3	155	-6	-127	-22	4.5	3.8
64	4	23	9	-32	0	1.1	0.8
65	5	93	-2	-77	-13	2.7	2.2
66	6	27	12	-20	-19	0.7	0.9
67	7	129	0	-90	-39	3.2	3.1
		S7 Mun. 8-14 June 1995 Wheat					
68	1	96	0	-85	-11	3.0	3.3
69	2	18	10	-27	-1	0.9	1.1
70	3	126	-1	-106	-19	3.7	3.7
71	4	21	7	-22	-6	0.8	1.3
72	5	81	-3	-67	-11	2.4	2.1
73	6	23	11	-18	-16	0.6	1.3
74	7	105	0	-80	-25	2.8	2.9
		S8 Mun. 31 May - 6 June 1997 Wheat					
75	1	185	-14	-166	-5	5.9	5.6
76	2	162	-6	-144	-12	5.1	4.7
77	3	84	2	-82	-4	2.9	2.5
78	4	42	3	-39	-6	1.4	1.4
79	5	163	-3	-139	-22	4.9	4.3
80	6	167	-6	-159	-1	5.6	4.8
81	7	180	-5	-174	-1	6.1	5.8

X - the number of the measuring day in the whole set, *x* - number of the measuring day in one session, *T* - air temperature, *e* - water vapor pressure, *u* - wind speed, *f* - relative air humidity, *P* - precipitation.

T a b l e 5. Heat balance components and evapotranspiration data for 8 measuring sess. S1..S8 (81 days), Tur. - Turew, Mun. - Müncheberg

X	*x*	Meteorological data (daily averages)					
		Rn	*G*	*LE*	*S*	*ETR* (*B*)	*ETR* (*T*)
		(W m^{-2})				(mm day^{-1})	
S1 Tur. 2-11 September 1995 Alfalfa							
1	1	48	2	-37	-13	1.3	1.6
2	2	30	6	-44	9	1.6	1.2
3	3	61	2	-61	-2	2.2	2.3
4	4	30	6	-31	-4	1.1	0.9
5	5	71	-4	-57	-11	2.0	1.2
6	6	102	-2	-76	-24	2.7	1.8
7	7	28	5	-23	-10	0.8	1.3
8	8	12	5	-17	0	0.6	1.2
9	9	106	-4	-81	-21	2.9	2.6
10	10	109	-4	-83	-21	2.9	2.1
S2 Tur. 2-11 September 1995 Bare soil							
11	1	51	-3	-28	-20	1.0	0.9
12	2	26	-1	-33	8	1.2	0.6
13	3	56	-5	-39	-11	1.4	1.3
14	4	31	-1	-11	-18	0.4	0.6
15	5	58	-3	-13	-42	0.4	1.2
16	6	85	0	-28	-57	1.0	1.7
17	7	29	0	-12	-17	0.4	0.7
18	8	10	0	-10	6	0.4	0.2
19	9	84	-8	-41	-35	1.4	1.9
20	10	88	-7	-32	-48	1.1	2.1
S3 Tur. 9-24 September 1997 Bare soil							
21	1	50	-3	-26	-22	0.9	1.2
22	2	82	1	-35	-48	1.2	1.8
23	3	77	4	-40	-40	1.4	1.8
24	4	47	2	-44	-5	1.6	1.2
25	5	30	3	-19	-14	0.7	0.5
26	6	60	3	-50	-12	1.8	1.3
27	7	93	2	-74	-21	2.6	1.8
28	8	63	2	-43	-23	1.5	1.4
29	9	14	3	-15	-2	0.5	0.5
30	10	39	4	-22	-20	0.8	0.8
31	11	61	3	-32	-32	1.1	1.2
32	12	48	2	-27	-23	1.0	1.1
33	13	52	5	-37	-20	1.3	1.1
34	14	56	4	-36	-23	1.3	1.2
35	15	14	5	-11	-8	0.4	0.4
36	16	9	5	-10	-4	0.3	0.2
S4 Tur. 9-24 September 1997 Sugar beats							
37	1	48	5	-54	0	1.9	1.5
38	2	75	2	-69	-8	2.4	2.4
39	3	62	6	-67	-1	2.4	2.3
40	4	49	3	-56	5	2.0	1.6
41	5	26	4	-25	-5	0.9	1.9
42	6	53	4	-59	2	2.1	1.1
43	7	74	3	-72	-4	2.5	2.3
44	8	53	4	-60	3	2.1	1.8
45	9	15	5	-29	9	1.0	1.3
46	10	35	7	-44	2	1.5	1.0
47	11	54	5	-61	1	2.2	1.7
48	12	47	5	-56	4	2.0	1.6
49	13	47	4	-58	7	2.0	1.4
50	14	52	4	-70	14	2.5	1.8
51	15	15	6	-25	4	0.9	0.6
52	16	8	5	-13	0	0.4	0.2
S5 Mun. 8-15 June 1994 Oat							
53	1	179	-4	-166	-9	5.9	6.0
54	2	43	13	-65	9	2.3	2.5
55	3	122	5	-114	-14	4.0	3.2
56	4	159	3	-133	-29	4.7	4.5
57	5	232	-1	-203	-28	7.2	6.1
58	6	68	9	-62	-14	2.2	2.1
59	7	160	1	-143	-17	5.0	5.4
60	8	210	5	-179	-36	6.3	6.2
S6 Mun. 8-14 June 1995 Sunflower							
61	1	118	-1	-94	-23	3.3	3.4
62	2	25	10	-31	-4	1.1	0.8
63	3	155	-6	-127	-22	4.5	3.8
64	4	23	9	-32	0	1.1	0.8
65	5	93	-2	-77	-13	2.7	2.2
66	6	27	12	-20	-19	0.7	0.9
67	7	129	0	-90	-39	3.2	3.1
S7 Mun. 8-14 June 1995 Wheat							
68	1	96	0	-85	-11	3.0	3.3
69	2	18	10	-27	-1	0.9	1.1
70	3	126	-1	-106	-19	3.7	3.7
71	4	21	7	-22	-6	0.8	1.3
72	5	81	-3	-67	-11	2.4	2.1
73	6	23	11	-18	-16	0.6	1.3
74	7	105	0	-80	-25	2.8	2.9
S8 Mun. 31 May - 6 June 1997 Wheat							
75	1	185	-14	-166	-5	5.9	5.6
76	2	162	-6	-144	-12	5.1	4.7
77	3	84	2	-82	-4	2.9	2.5
78	4	42	3	-39	-6	1.4	1.4
79	5	163	-3	-139	-22	4.9	4.3
80	6	167	-6	-159	-1	5.6	4.8
81	7	180	-5	-174	-1	6.1	5.8

X - the number of the measuring day in the whole set, *x* - number of the measuring day in one session, *Rn* - net radiation, *S*- sensible heat flux, *G* - soil heat flux, *ETR (B)* - evapotranspirat. measured by the Bowen's ratio, *ETR*(*T*) - evapotranspiration modelled by theTHESEUS.

T a b l e 6. The average or sum of meteorological parameters and heat balance components as well as evapotranspiration measured (*ETR*(*B*)) or simulated (*ETR*(*T*)) for 8 measurement sessions (sess.) S1..S8

Sess. (no.of days)	*T* (°C)	*e* (hPa)	*u* ($m\ s^{-1}$)	*f* (%)	*P* (mm)	*Rn*	*G*	*LE*	*S*	Bowen's ratio	*ETP*	*ETR*(*B*)	*ETR*(*T*)	*ETR*(*B*)/ *ETP* (average)
						($W\ m^{-2}$)					(sum of the session) ($mm\ session^{-1}$)			
S1(10)	14.2	13.4	2.3	83	17.5	60	1	-51	-10	0.19	21.3	18.0	16.2	0.84
S2(10)	14.2	13.3	2.4	83	17.5	52	-3	-24	-24	0.97	20.6	8.6	11.2	0.41
S3(16)	9.4	9.6	2.6	82	27.0	50	3	-33	-20	0.61	26.9	18.4	17.5	0.68
S4(16)	9.3	9.8	2.4	84	25.2	45	4	-51	2	-0.04	22.8	28.8	24.5	1.26
S5(8)	13.5	11.9	2.4	77	7.1	147	4	-133	-17	0.13	34.2	37.6	36.0	1.10
S6(7)	13.3	12.7	1.7	89	52.1	81	3	-67	-17	0.26	14.4	16.6	15.0	1.15
S7(7)	13.2	12.8	1.8	90	52.3	67	3	-58	-13	0.22	13.2	14.3	15.7	1.08
S8(7)	16.6	14.5	1.4	56	14.6	140	-4	-129	-7	0.06	30.6	31.9	29.1	1.04
Avr. sum	12.3	11.8	2.2	81	2.6	72	2	-61	-13	0.21	2.3	2.1	2.0	0.95
Whole period					213.2						184.0	174.1	165.2	

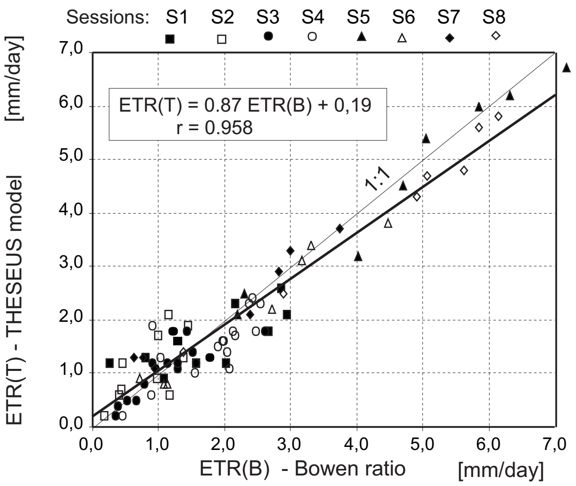

Fig. 4. Comparison of evapotranspiration simulated by the THESEUS (*ETR*(*T*)) and calculated from the latent heat measured by the use of the modified Bowen's ratio method (*ETR*(*B*)).

In Table 7, results of the statistical analysis are presented for all 8 measuring sessions separately, linear regression coefficients and correlation coefficients were combined. Additionally, the relative estimation error for all individual measuring sessions was added.

In the case of the three sessions, the relative estimation error was equal to or higher than 10 %. The measurements of the session 1 and 2 were carried out at two fields (S1 alfalfa, S2 bare soil) at the same time from 2 September 1995 to 11 September 1995. The summer of 1995 was extremely dry (only about 40% of long term average precipitation occurred). The measured cumulative evapotranspiration of alfalfa was 18.0 mm, while the simulated value was 16.2 mm. The estimation of evapotranspiration by the THESEUS model is based on the calculations of soil moisture of the upper layer (0-90 cm). That is probably the reason why the THESEUS underestimated daily evapotranspiration. The upper soil layer in that summer was very dry but alfalfa had a very deep root system, which allowed to use soil water from deeper layers. Under such extreme precipitation conditions, the relative error of the THESEUS estimation is still on an acceptable level. At the same time, measurements were carried out on bare soil (session S2). This time, the evapotranspiration estimation by the THESEUS was higher by about 30%. The measuring site was called bare soil but in fact about 30-40% of the field was covered with straw (lying in rows after harvesting). The straw layer decreased evaporation rate significantly (under the straw the soil was wet). The THESEUS model structure does not allow for an inclusion of such conditions (straw on bare soil) and consequently, for that period (session S2) the model estimation was made for bare soil. So, a very high relative error of evapotranspiration estimation for the session S2 (-30%) resulted not from an incorrect parameterization for the bare soil used in the THESEUS but rather from the absence of an appropriate part in the THESEUS model (bare soil partly covered by straw).

For the session S4, there was also a relatively high error of evapotranspiration estimation by the model (14.9%). The field was covered with sugar beets in good condition and was located close to the bare soil field. The sugar beets still required water and were able to evapotranspire more than 2 mm per day. The weather during this session was not too warm and the net radiation was lower than normal. Consequently, energy deficit for evapotranspiration could only be accounted for by advected sensible heat. The average sensible heat flux density during the measuring session S4 was the only one with positive values (on the

T a b l e 7. Coefficients for the linear comparison of *ETR*(*B*) and *ETR*(*T*) for 8 measuring sessions- *ETR*(*T*) = a *ETR*(*B*) + *b*

Measuring session number (*x*) no of days	a	b	Correlation coefficient r	Relative error of estimation for the individual session (%)
S1(10)	0.398	0.938	0.719	10.0
S2(10)	0.836	0.434	0.702	-30.0
S3(16)	0.710	0.278	0.820	4.9
S4(16)	0.698	0.272	0.749	14.9
S5(8)	0.901	0.266	0.960	4.2
S6(7)	0.907	-0.007	0.975	9.6
S7(7)	0.826	0.556	0.972	-9.8
S8(7)	0.914	-0.005	0.990	8.7
Whole set	0.868	0.186	0.958	5.1

average +2 W m^{-2}, Table 6). The maximum value of the sensible heat coming from atmosphere to the sugar beet field was 14 W m^{-2} on 22 September 1997 (Table 5). For the whole session S4, the ratio *ETR*/*ETP* was equal to 1.26 (Table 6). Comparison of *ETR*(*B*) and *ETR*(*T*) for the session S4 suggests that if the THESEUS is used for evapotranspiration estimation on the landscape scale, special attention should be paid to the areas with possible advection, otherwise the estimation error can be significantly high.

The relative error of estimation (*REE*) of the daily evapotranspiration rate (Eq. (16)) decreased with increasing daily evapotranspiration rate. If the daily rate of evapotranspiration is low (0.5 mm or less), then the relative error can be very high (for 0.5 mm about 45%). The measuring points with high relative error come mainly from the session S2 (bare soil with straw). The reason for such a poor estimation for this session was described earlier. There are also some measuring points with high error of estimation in other sessions, but the daily evapotranspiration rate for these days is very low (0.4 to 0.8 mm day^{-1}). Although these estimations show a very high error, because of a very low *ETR*, it does not significantly influence the evapotranspiration estimation for a longer period (week, month or season). For higher evapotranspiration rates, evapotranspiration estimated by the model shows a very good agreement with measurements. For the daily evapotranspiration rate from 2 to 4 mm day^{-1}, the average relative error of estimation is about 10% and for higher rates, the error is even smaller. It means that for the conditions, which increase evapotranspiration (high soil moisture, warm, windy, high *Rn* and well developed plant canopy), a very good parameterization was achieved. For such conditions, the relative error of the daily rate of the modelled evapotranspiration is about 7%. On 12 June 1994 (session S5 -oat), the highest evapotranspiration was measured, 7.2 mm day^{-1} (Table 5). There was no advection during that day (the average sensible heat flux density was -28 W m^{-2}). The value of 7.2 mm day^{-1} is close to the maximum value that is possible under Central European climatological conditions (without advection). Even for such a day (extreme high net radiation), the THESEUS simulation showed a very good agreement with the measurements: *ETR*(*T*) is equal to 6.1 mm day^{-1}, which is only 15% less then measured.

Finally, changes of the average relative error of estimation (*AREE*) of the evapotranspiration simulation by the THESEUS model was calculated as a function of integration time. In Fig. 5, the results of such an analysis are shown for the whole data set (81 days). The time of integration for the calculations of *AREE* was extended to the length of the whole period of investigation (Fig. 5). It can be seen, that if *AREE* is calculated for the whole set of data, it decreases rapidly: starting from about 25 % for one day of integration time to 5.1% for 80 days time of integration. When the session 2 was not taken into consideration (this is again the "straw problem") *AREE* was even smaller, equal to 3.9%.

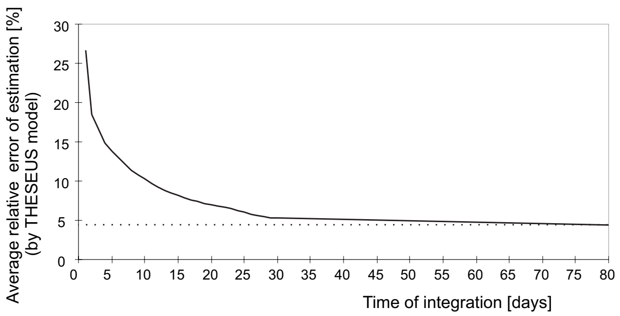

Fig. 5. Relative error of evapotranspiration estimation by the THESUS model as a function of integration time on the basis of the whole data set (81 days).

CONCLUSIONS

The THESEUS model developed at the ZALF, is a very high quality tool for the estimation of evapotranspiration at various scales: from field to landscape, if the required input data are available. On the basis of the measuring results from the modified Bowen's ratio method and the THESEUS modelling procedure, the following conclusions can be drawn:

1. It is possible to control quality of the measuring results of the heat balance components in patchy landscapes, using modification of the Bowen's ratio method.

2. The relative error of the evapotranspiration estimation (*REE*) by THESEUS model is lower for higher daily evapotranspiration rates. The average error (*AREE*) is about 10% for 10 days of the integration time and decreases to about 5% for longer time of integration.

3. In order to achieve a better agreement between the measured and modelled evapotranspiration values, a correction equation should be used (on the average *ETR*(*T*) was lower then *ETR*(*B*) by 0.1 mm day^{-1}, $ETR(T) = 0.87\ ETR(B) - 0.19$).

4. In the future, further parts of water balance estimation should be added to the model, because so far, in the THESEUS there has been no possibility to model evaporation of bare soil covered with straw.

ACKNOWLEDGMENT

The project was supported by the German-Polish scientific co-operation Program.

The authors are grateful to their colleagues from ZALF, RCAFE and ADAU for their help during measurements sessions. A special thanks to Dr. Wegehenkel for his assistance during the use of the THESEUS model.

REFERENCES

Beljaars A.C. and Holtslag A.A.M., 1991. Flux parameterization over land surfaces for atmospheric models. J. Appl. Meteor., 3, 327-341.

Black T.A. and McNaughton K.G., 1971. Psychrometric apparatus for Bowen ratio determination over forests. BLM, 1, 246-254.

Ferré P.A., Knigth J.H., Rudolph D.L., and Kachanoski R.G., 1998. The sample areas of conventional and alternative time domain reflectometry probes. Water Resour. Res., 34, 2971-2979.

Glugla G., 1969. Berechnungsverfahren zur Ermittlung des aktuellen Wassergehaltes und Gravitationsabflusses. Albrecht-Thaer-Archiv, 13, 371-376.

Haude W., 1955. Zur Bestimmung der Verdunstung auf möglichst einfache Weise. Mitt. des Deutschen Wetterdienstes, 11, Bad Kissingen.

Holtslag A.A.M. and Van Ulden A.P., 1983. A simple scheme for daytime estimates of the surface fluxes from routine weather data. J. Appl. Meteor., 22, 517-529.

Holtslag A.A.M. and De Bruin H.A.R., 1988. Applied modelling of the nighttime surface energy balance over land. J. Appl. Meteor., 27, 659-704.

Jenkins D.R., 1989. Improved field probes for soil water content and electrical conductivity measurements using time domain reflectometry. Water Resour. Res., 25, 2367-2376.

Koitzsch R. and Günther R., 1990. Modell zur ganzjährigen Simula- tion der Verdunstung und der Bodenfeuchte landwirtschaftlicher Nutzflächen. Arch. Acker-Pflanzenbau Bodenkd., 24, 717-725.

Kovacs G., 1988. Comparison of models interrelating multiannual precipitation and actual areal evapotranspiration. J. Hydrol., 66, 1-76.

Kundzewicz Z.W., 1990. Water sciences at the threshold of the 21st century; are we preparing sufficiently for the global changes likely to occur? Proc. Commemorative Symp. 25 yrs. of IHD/IHP. Unesco, Paris, 159-167.

McNaughton K.G. and Spriggs W.T., 1985. A mixed-layer model for regional evaporation. BLM, 34, 243-262.

Monteith J.L., 1975. Vegetation and the Atmosphere. Principles. Academic Press, London, 1, 278.

Monteith J.L. and Unsworth M.H., 1990. Principles of Environmental Physics. Edward Arnold, New York.

Morton F.J., 1983. Operational estimates of evapotranspiration and their significance to the science and practice on hydrology. J. Hydrol., 66, 1-76.

Olejnik J., 1996. Catchment scale modelling of heat and water balance structure under present and future climatic conditions (in Polish). Rocz. AR, Poznań, 268, 125.

Olejnik J., 1988a: Present and future estimates of evapotranspiration and runoff in Europe. IIASA Working Pap. WP-88-037, 15.

Olejnik J., 1988b. The empirical method of estimating mean daily and mean ten-day values of latent and sensible-heat near the ground. J. Appl. Meteorol., 12, 1358-1369.

Olejnik J. and Kędziora A., 1991. A model for heat and water balance estimation and its application to land use and climate variation. Earth Surface Proc. Landforms, 16, 601-617.

Penman H.L., 1948. Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. London, A, 193, 120-145.

Renger M., O. Strebel K., and Giesel W., 1974. Beurteilung bodenkundlicher, kulturtechnischer und hydrologischer Fragen mit Hilfe von klimatischer Wasserbilanz und bodenphysikalischen Kennwerten 1.Bericht: Beregnungsbedürftigkeit. Z.f.Kulturtechnik u. Flurbereinigung, 15, 3.

Sellers P.J. and Dorman J.L., 1986. Testing the simple biosphere model (SiB) using point micrometeorological and biosphere data. J. Clim. Appl. Meteorol., 26, 622-651.

Spittlehouse D.L. and Black T.A., 1981. A comparison of reversing psychrometric Bowen ratio measurement systems. Atmosphere-Ocean, 19, 372-379.

Sponagel H., 1980. Zur Bestimmung der realen Evapotranspiration landwirtschaftlicher Kulturpflanzen. Geol. Jahrbuch, Reihe F, Hannover, 9.

Stenitzer E., 1988. Ein numerisches Modell zur Simulation des Bodenwasserhaushaltes und des Pflanzenertrages eines Standortes. Mitt. aus der Bundesanstalt für Kulturtechnik und Bodemwasserhaushalt, 31.

Ten Berge, H.F.M., Metselaar, K., Jansen, M.J.W., San Agustin, E.M., and Woodhead T., 1995. The Sawah riceland hydrology model. Water Resour. Res., 31, 11, 2721-2731.

Thom A.S. and Oliver H.R., 1977. On Penman's equation for estimating regional evaporation. Q. J. R. Meteorol. Soc., 103, 345-357.

Topp G.C. and Davis J.L., 1985. Measurements of soil water content using time-domain reflectometry (TDR): A field evaluation. Soil Sci. Soc. Am. J., 49, 19-24.

Topp G.C., Davis J.L., and Annan A.P., 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water Resour. Res., 16, 574-582.

Turc L., 1961. Evaluation des besoins en eau d'irrigation evapotranspiration potentielle. Ann. Agron., 12, 13.

Van De Griend A.A. and Van Boxel J.H., 1989. Water and surface energy balance model with a multilayer canopy representation for remote sensing purpose. Water Resour. Res., 25, 949-971.

Wendling U., Schellin, H.G., and Thomä M., 1991. Bereitstellung von täglichen Informationen zum Wasserhaushalt des Bodens für die Zwecke der agrarmeteorologischen Beratung. Z. f. Meteorologie, 41, 6, 1-16.

Wegehenkel M., 1997a. SVAT-Modellierung auf GIS-Basis am Beispiel der Agrarlandschaft Chorin. Arch. für Nat.-Lands. 36, 149-164.

Wegehenkel M., 1997b. Validierung von Bodenwasserhaushaltsmodellen mit Hilfe von TRIME-TDR, Tensiometermessungen sowie gravimetrischen Feuchtebestimmungen, Z. Pflanzenenrnähr. Bodenk., 161, 583-590.

Wegehenkel M., 2000: Test of modelling system for simulating water balances and plant growth using various different complex approaches. Ecological Modelling, 129, 39-64.