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INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Int. Agrophys., 2016, 30, 231-235
doi: 10.1515/intag-2015-0092

Modified method of aerodynamic resistance calculation and its application to potential evapotranspiration estimation**

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Received December 14, 2015; accepted May 4, 2016

A b s t r a c t. The aim of this study was to present and validate an alternative evapotranspiration calculation procedure that includes specific expression for the aerodynamic resistance. Calculated daily potential evapotranspiration totals were compared to the results of FAO56 procedure application and to the results of measurements taken with a precision weighing lysimeter permanently grown with irrigated, short grass. For the examination period from March 17 through October 31, 2011, it was found that daily potential evapotranspiration estimates obtained by both calculation procedures fitted well to the lysimeter measurements. Potential evapotranspiration daily totals calculated with the use of the proposed aerodynamic resistance calculation procedure gave better results for days with higher evapotranspiration, compared to the FAO56 method. The most important is that the approach based on the proposed alternative aerodynamic resistance could be effectively used even for a wide variety of crops, because it is not limited to any particular crop.

K e y w o r d s: potential evapotranspiration, reference evapotranspiration, grass, aerodynamic resistance, lysimeter

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**This work was partially supported by grant agency APVV, grant 0512-12, and by grant agency of the Slovak Academy of Sciences VEGA, projects 2/0032/13 and 2/0083/11. This publication is the result of the project implementation ITMS 26240120004, Centre of excellence for integrated flood protection of land, supported by the Research and Development Operational Programme funded by the ERDF.

INTRODUCTION

Proper evapotranspiration (E) estimates are essential for energy and water balance studies, climate modelling, irrigation planning, quantification of agricultural production, and many other purposes (Gong *et al.*, 2006; Pitman, 2003; Monteith and Unsworth, 1990; Sellers *et al.*, 1997). Consequently, poor and non-representative evapotranspiration estimates could lead to misleading conclusions, with significant economic consequences (Allen *et al.*, 2011).

Information about evapotranspiration can be obtained from a wide range of measurement systems, including weighing lysimeters, eddy covariance, Bowen ratio, and even satellite-based remote sensing. However, those measuring methods are usually complicated in application, the measuring equipment is expensive, and their results can differ considerably from each other. Therefore, several calculation procedures based on meteorological parameters have been proposed in literature (Allen *et al.*, 1998; Hargreaves and Samani, 1985; Monteith 1965; Novák, 2012; Penman, 1948; Priestley and Taylor, 1972).

Penman (1948) defined the potential evapotranspiration (E_p) as 'the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile'. The equation proposed by Penman is known as Penman equation. In this approach, the evapotranspiration rate was not related to any specific crop, and in fact there are many types of crops that fit into the description.

Following the studies of Jensen *et al.* (1970), Doorenbos and Pruitt (1977), Perrier (1985) and Smith *et al.* (1992), the expert consultation recommended the concept of reference evapotranspiration (ET_o) defined as 'the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance r_c = 70 s m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground'. Moreover, experts recommended the adoption of the Penman-Monteith equation (*PM*) for estimating ET_o (Allen *et al.*, 1998). The standardized procedure is described in detail in the FAO Irrigation and Drainage Paper No. 56 'Crop Evapotranspiration', generally referred to as the FAO56.

Once ET_o is calculated, it can be further adjusted by an empirical crop coefficient (K_c) to evaluate potential or actual crop evapotranspiration (ET_c). Direct determination of ET_c by the *PM* equation is constrained by the need to determine the 'bulk' surface resistance (r_c), the resistance to water vapour flow through the surface of the transpiring canopy.

Several approaches have been suggested for operational determination of the r_c parameter, often recognized as a biophysical *ET* controller (Jarvis, 1976; Katerji and Rana, 2006; Lecina *et al.*, 2003; Todorovic, 1999). However, presented formulas of r_c calculation are valid for a particular canopy and location only (Katerji and Rana, 2011).

Another alternative modification to calculate potential evapotranspiration of different canopies was proposed by Novák and Hurtalová (1987), following studies of Budagovsky (1964) and Zilitikievich and Monin (1971). The potential evapotranspiration of well-watered canopy was calculated using the Penman-Monteith equation (*PM*) (with r_c = 0) and the aerodynamic resistance term (r_a) expressed according to the modified approach of Zilitinkievich and Monin (1971). This approach, in principle, allows calculations of potential evapotranspiration E_p also for non-reference, well watered canopies.

The aim of this study was:

– to present a calculation procedure of potential evapotranspiration of various canopies, using modified expression of the aerodynamic resistance to vapour flow, based on the proposal of Zilitinkievich and Monin (1971); and
– to compare the results of the proposed calculation procedure to the FAO56 method and to the results of weighing lysimeter measurements.

Close results of daily potential evapotranspiration totals E_p estimated by both calculation procedures could lead to the development of a relatively simple procedure for the calculation of E_p of various canopies.

MATERIAL AND METHODS

The FAO56 standardized procedure adopts the Penman–Monteith equation (Allen *et al.*, 1998) in the following form:

$$E = \frac{1}{\lambda}\frac{\Delta(R_n - G) + \rho_a c_p D / r_a}{\Delta + \gamma(1 + r_c / r_a)}, \qquad (1)$$

where: E is the evapotranspiration (mm day^{-1}), R_n is the net radiation at the evaporation surface level (W m^{-2}), G is the soil heat flux (W m^{-2}), ρ_a is the mean air density at constant pressure (kg m^{-3}), c_p is the specific heat of the air (J kg^{-1} C^{-1}), r_c is the bulk canopy resistance (s m^{-1}), r_a is the aerodynamic resistance (s m^{-1}), Δ is the slope of the saturation vapour pressure versus temperature relationship (kPa °C^{-1}), D is the vapour pressure deficit of the air (kPa), λ is the latent heat of vaporisation (J kg^{-1}), and γ is the psychrometric constant (kPa °K^{-1}).

The aerodynamic resistance to water vapour flow in the FAO56 calculation procedure is expressed as:

$$r_a = \frac{\ln\left[\frac{z_m - d_e}{z_{om}}\right]\ln\left[\frac{z_h - d_e}{z_{oh}}\right]}{\kappa^2 u_z}, \qquad (2)$$

where: z_m, z_h are the heights of the wind speed and air temperature measurements (m), d_e is the zero plane displacement height (m) estimated by $d_e = 0.67h_c$, where h_c means the height of the crop (m); z_{oh} is the roughness length governing the transport of the and vapour (m), z_{om} is the roughness length governing momentum transfer (m), u_z is the wind velocity at height z (m s^{-1}), and κ is the von Karman constant (-), κ = 0.41 was used in this study.

The applicability of the Penman-Monteith Eq. (1) is strongly limited by the knowledge of bulk canopy resistance r_c which depends on canopy properties as well as on leaf water potential. Bulk canopy resistance is characteristic for a particular canopy under particular conditions, and its application to other conditions is not recommended (Jarvis, 1976; Katerji and Rana, 2006). Another possibility to calculate potential evapotranspiration is set r_c = 0, *ie* evapotranspiration from wet canopy is assumed. Aerodynamic resistance is denoted as r_{a_e}. Then, the Penman-Monteith equation can be expressed in the form:

$$E_p = \frac{1}{\lambda}\frac{\Delta(R_n - G) + \rho_a c_p D / r_{a\_e}}{\Delta + \gamma}. \qquad (3)$$

Based on the Bowen ratio measurements above the grass canopy, Zilitikievich and Monin (1971), and Budagovsky (1981), expressed normalized distribution of air humidity, air temperature and wind velocity in sublayers (0, z_o) and (z_o, z). Based on those distributions, the aerodynamic resistance to water vapour transport was expressed as a sum

of resistances characterizing two horizontal air layers embracing the height intervals (0, z_o) and (z_o, z). In this concept, the evaporation starts directly at the evaporating surface (z=0) and not at the height characterized by the roughness length (z_o), which is in contrast with the FAO56 methodology. The evaporating surface is assumed to be at the 'effective height of the canopy' or the 'zero displacement level', which means the same height. This approach (as well as Penman, 1948) characterizes evapotranspiration from wet surface.

For the equilibrium state of the atmosphere, the aerodynamic resistance to water vapour transport in the viscous sublayer, defined by the height interval (0, z_o), can be evaluated using the empirical form relating the aerodynamic resistance to the Reynolds number (Zilitikievich and Monin, 1971). The generalized equation for the lower sublayer (0, z_o) can be expressed in the following form:

$$r_{a\_sub} = \frac{\left(\frac{z_o u_*}{\nu_a}\right)^{p_e}}{\kappa u_*}, \qquad (4)$$

where: u_* is the friction velocity (m s^{-1}), z_o is the crop specific roughness length of the evaporating surface (m), υ_a is the kinematic viscosity of the air (m^2 s^{-1}), and p_e is an empirical parameter, slightly dependent on canopy properties and on the state of the atmosphere. Zilitinkievic and Monin (1971) use a constant value close to 0.5 (-), p_e= 0.45 was used in this study. Expressions for friction velocities together with the crop specific roughness lengths could be found in the monograph by Novák (2012).

The resistance to water vapour transport in the boundary layer above the canopy, defined by the height interval (z_o, z), can be evaluated using the empirical form suggested by Thom (1972, 1975). When assuming the roughness length parameters for transport of heat (z_{oh}) and momentum (z_{om}) equal (z_{om}=z_{oh}), it can be assigned as z_o; the resistance in the boundary layer (z_o, z) can be expressed in the following form:

$$r_{a\_b} = \frac{\ln\left(\frac{z - d_e}{z_o}\right)}{\kappa u_*}, \qquad (5)$$

where: z is the height of wind velocity measurements, d_e is the zero plane displacement height (m).

Alternatively, the specific expression of the aerodynamic resistance (r_{a_e}) of the layer (0, z), that combines the aerodynamic resistance to water vapour transport in the sublayer (z_o, z) and in the boundary layer just above the canopy (0, z_o), can be expressed in the form:

$$r_{a\_e} = \frac{\left(\frac{z_o u_*}{\nu_a}\right)^{p_e} + \ln\left(\frac{z_2 - d_e}{z_o}\right)}{\kappa u_*}. \qquad (6)$$

The parameters are the same as described above (*ie* Eqs 4 and 5). Roughness lengths in Eq. (6) are z_o which is the roughness length governing the momentum transport (it can be estimated from wind velocity profiles). As it was mentioned, for neutral state of the atmosphere p_e= 0.45 is a good approximation.

Reference evapotranspiration was measured by means of a weighing lysimeter facility at the experimental site of the University of Natural Resources and Life Sciences, Vienna (BOKU). The experimental site is located in Gross-Enzersdorf (48°12'N, 16°34'E; 157 m a.s.l.) in the north-eastern part of Austria. The lysimeter surface and its surroundings are grown with grass that is cut and irrigated frequently. The main part of the lysimeter facility consists of a cylindrical vessel with an inner diameter of 1.9 m (surface area A= 2.85 m^2) and a hemispherical bottom with a maximum depth of 2.5 m, packed with sandy loam soil (0-140 cm) over gravel (140-250 cm) (Neuwirthand Mottl, 1983). A mechanical weighing system transmits a fractional amount of the lysimeter mass to an electronic load cell. The analogue output signal of the load cell is amplified and converted to digital units (Nolz *et al.*, 2011). Weighing data are measured every few seconds, averaged and stored every 10 min. As a consequence, changes of water mass in the lysimeter (ΔW_{lys}) can be determined for a certain time interval. During dry spells, the lysimeter is additionally irrigated to meet the grass maximum water requirements (Nolz *et al.*, 2013).

Meteorological parameters for evapotranspiration calculations were obtained from the on-site standard reference weather station of the Central Institute for Meteorology and Geodynamics, Austria (ZAMG), the standard type instruments of which are situated nearby the lysimeter. Details can be found in a paper of Nolz *et al.* (2013). The meteorological parameters measured included solar radiation R_s (MJ m^{-2} h^{-1}), maximum and minimum air temperatures at 2 m height T_{max},T_{min} (°C), relative humidity at 2 m height r (%), wind velocity at 10 m height u_{10} (m s^{-1}), and precipitation P (mm). The wind velocity at 2 m height was determined using the wind profile relationship as presented in Allen *et al.* (1998). Net radiation (R_n) was determined from the measured solar radiation (R_s) according to Allen *et al.* (1998), and used in both calculation procedures. Experimental data available for this study were collected from the 17th of March through the 31st of October, 2011.

RESULTS AND DISCUSSION

The method of FAO56 (Allen *et al.*, 1998) allows to calculate the reference evapotranspiration and then to calculate potential evapotranspiration of various canopies using their crop coefficient.

The method proposed aims to calculate potential evapotranspiration of various canopies without knowing the 'bulk' canopy resistance r_c (Eq. (1)) which is difficult to

obtain (Jarvis, 1976). Then, it is assumed that r_c=0, valid for wet surfaces. Differences in the values of r_c could lead to differences in E_p, therefore it was necessary to check it by comparing the results of both calculation methods and the results of the lysimetric measurements, as well as to evaluate the differences. The close results of the measured and calculated daily potential evapotranspiration totals of grass showed that the differences were small and acceptable. Hence, it follows that the proposed method could be acceptable for the calculation of potential evapotranspiration of various canopies.

Daily reference evapotranspiration was calculated using Eq. (1) with aerodynamic resistances expressed by Eq. (2). The potential evapotranspiration of wet grass canopy was calculated using Eq. (3), with aerodynamic resistances expressed by Eq. (6). Comparisons of the daily evapotranspiration totals calculated by both procedures to the evapotranspiration of irrigated grass measured by means of the lysimeter are presented in Figs 1 and 2.

As it is shown in Figs 1 and 2, both calculation procedures gave estimates of evapotranspiration daily totals which fit well to the data obtained from the lysimeter. While the FAO56 method slightly outperformed the proposed method during days with high evapotranspiration, the opposite was true for days with low evapotranspiration. Due to this, more significant scatter and a slightly lower coefficient of determination were obtained for the FAO56 method (Figs 1 and 2).

The presented results indicated that the scatter of the average daily values of ET_o calculated by FAO56 and by the proposed method depend slightly on the prevailing meteorological conditions. The scatter of the calculated evapotranspiration daily totals (Fig. 1) is more pronounced during days with higher air temperatures (higher radiation

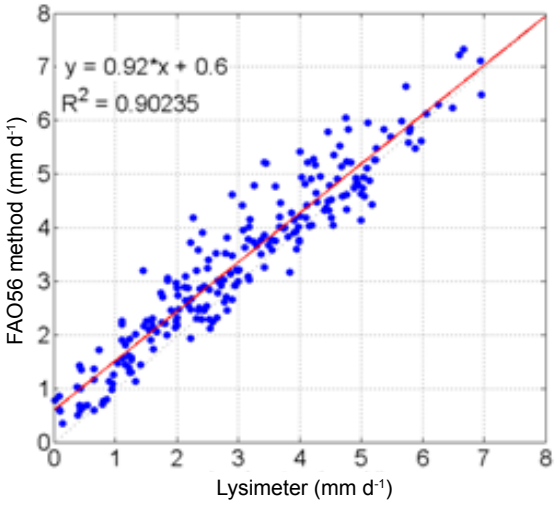

Fig. 1. Daily reference evapotranspiration ET_o during the growing season, calculated by the FAO56 procedure, and daily evapotranspiration of irrigated grass measured by means of the weighing lysimeter.

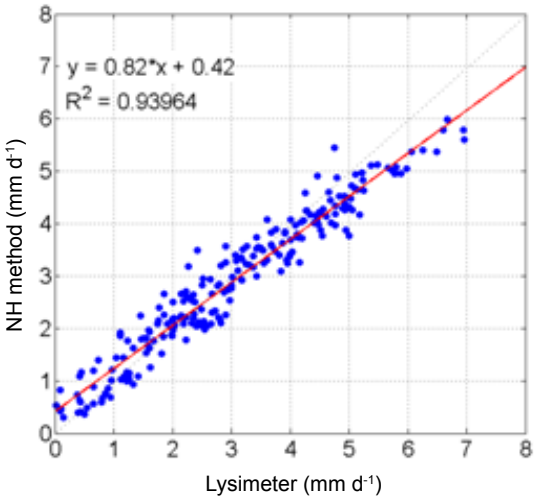

Fig. 2. Daily potential evapotranspiration E_p during the growing season, calculated by the proposed procedure, and evapotranspiration of irrigated grass measured by means of the weighing lysimeter.

terms), when calculated by the FAO56 method, in comparison to the proposed method using aerodynamic resistance term (Fig. 2). Therefore, this indicates a superiority of the proposed procedure for the calculation of daily reference evapotranspiration totals over the FAO56 method. It can be mentioned that all the methods of evapotranspiration calculation are approximate, *ie* some differences between measured and calculated data are expected. The main reasons are the difficulties with the estimation of adequate input data, characterizing the system, but even the method of aerodynamic resistance calculation can be important.

It was shown in this study that the FAO56 method and the proposed one can give close results, comparable to the results of lysimetric measurements of well-watered grass canopy evapotranspiration. This demonstrates the applicability of the proposed method to calculate potential evapotranspiration of a wide variety of crops. Moreover, the applicability of the proposed method is not limited by the knowledge of the canopy resistance, which could considerably simplify potential evapotranspiration calculation procedure also for the non-reference canopies. This needs further research, which is complicated by the lack of measurement results for non-referenced canopies.

CONCLUSIONS

1. The results of two potential evapotranspiration calculation procedures (FAO56 and the proposed one) were analyzed, and daily totals of potential evapotranspiration were calculated and compared to the evapotranspiration of irrigated grass of the weighing lysimeter facility.

2. It was shown that daily reference (potential) evapotranspiration of grass canopy estimates by FAO56 and by the proposed method were close to the lysimeter values, but the proposed modified method gave values closer to the

measured ones. The proposed method, based on using the modified aerodynamic resistance calculation, can be used, in principle, even for non-reference canopies; this is the main advantage of the proposed procedure.

3. The application of the FAO56 method for non-reference canopies remains complicated due to the tedious determination of the surface resistance parameters. The results indicate that this problem could be partly resolved using the proposed approach.

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