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Comparison of daily potential evapotranspiration calculated by two procedures based on Penman-Monteith type equation

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Abstract. Paper presents comparison of the daily reference crop (grass vegetation cover) potential evapotranspiration results calculated by the two modifications of the Penman-Monteith type equation. The first modification was published in FAO recommendation (Allen at al., 1998), PM-FAO, the second is modification according to Budagovskiy (1964) and Novák (1995), PM-BN. Both are used in soil water simulation models HYDRUS-1D and GLOBAL. Calculations were performed for frost-free seasons of the years 2000–2009, using the meteorological station Gabčíkovo (South Slovakia) meteorological data and canopy characteristics. The results indicate significant differences in daily and seasonal potential evapotranspiration. Reasons for those differences are discussed; they should be in different net radiation and aerodynamic resistance estimation methods.

Keywords: Potential evapotranspiration; Reference crop; Penman-Monteith equation.

INTRODUCTION

Evapotranspiration is the key element of land water balance structure and its precise evaluation is decisive for its proper evaluation. Annual evapotranspiration of Slovak territory covers approximately two thirds of precipitation, in lowland regions it approaches 90 percent of the annual precipitation (Majerčáková and Šťastný, 2001).

Penman-Monteith (PM) equation and its modifications (Budagovskiy, 1964; Budagovskyi and Novák, 2011a, b; Monteith, 1965; Novák, 1989; Penman, 1948) are basic tools to calculate evapotranspiration. They are used mostly to calculate potential evapotranspiration and then to modify it to the actual one. There were indicated significant differences in results of mathematical modeling of water and energy transport in the Soil-Plant-Atmosphere System (SPAS), because the two mentioned different procedures based on modifications of the PM equation were used. One (Allen et al., 1998) is incorporated in the model HYDRUS-1D (Šimůnek et al., 2008), and the second in the model GLOBAL (Majerčák and Novák, 1992; Novák and Majerčák, 1992).

It was necessary to compare both approaches and find the reasons for the resulting differences. The best way how to do it, is to compare results of potential evapotranspiration of a reference crop (grass vegetation cover), calculated by both of the methods. This is the aim of this paper.

FAO Penman-Monteith equation (PM-FAO modification procedure)

Food and Agricultural Organization (FAO) procedure to calculate potential evapotranspiration ET_o is based on modification of Penman-Monteith equation in general form as it is implemented in the simulation model HYDRUS-1D (Šimůnek et al., 2008). It can be written:

$$ET_o = ET_r + ET_a = \\ = \frac{1}{\lambda}\left[\frac{\Delta\left(R_n - G\right)}{\Delta + \gamma\left[1+\left(r_c / r_a\right)\right]} + \frac{\rho_a . c_p\left(e_a - e_d\right)/r_a}{\Delta + \gamma\left[1+\left(r_c / r_a\right)\right]}\right], \tag{1}$$

where ET_o is the potential evapotranspiration rate expressed by a soil water layer thickness evaporated per day (mm d^{-1}), ET_r is „the radiation term” (mm d^{-1}), ET_a is „the aerodynamic term” (mm d^{-1}), Δ is the slope of the saturation vapor pressure curve as a function of temperature ($e_a = f(T)$) (kPa °C^{-1}), R_n is net radiation (MJ m^{-2}d^{-1}), G is the soil heat flux (MJ.m^{-2}d^{-1}), ρ_a is the air density (kg m^{-3}), c_p is the specific heat of moist air (kJ kg^{-1} °C^{-1}) (c_p =1.013 kJ kg^{-1} °C^{-1}), ($e_a - e_d$) is the vapor pressure deficit (kPa), e_a is the saturation water vapor pressure (kPa), e_d is the actual water vapor pressure (kPa), r_a is the aerodynamic resistance (s m^{-1}), λ is the latent heat of vaporization (MJ kg^{-1}), γ is the psychrometric constant (kPa °C^{-1}), r_c is the canopy resistance (s m^{-1}).

Sensitivity analysis has shown net radiation R_n as the most sensitive parameter in the Eq. (1). Evaporating surface is strongly influencing evapotranspiration through the two resistances r_a and r_c. Inversion term of resistances (used in some modifications of the Eq. (1)), is the velocity coefficient of the turbulent transport $D = 1/r_a$ (m s^{-1}).

Aerodynamic resistance r_a is expressed in the FAO procedure (Allen et al., 1998), as follows:

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

where z_m , z_h are heights of the wind speed and of the temperature and the humidity measurements (m), d_e is the zero plane displacement height (m), z_{oh} is the roughness length governing transport of the heat and the vapor (m), z_{om} is the roughness length governing momentum transfer (m), u_z is the wind speed at the height z (m s^{-1}), κ is the von Karman constant (–) (κ = = 0.41).

According to the FAO procedure of potential evapotranspiration calculation – ET_o is a reference evapotranspiration, calculated by the PM-FAO equation (Eq. (1)), (Allen et al., 1998). It is potential evapotranspiration of „reference“ grass canopy with height z_p = 0.12 m, canopy resistance r_c = 70 s m^{-1}, and albedo a = 0.23.

Aerodynamic resistance of reference canopy is expressed by Allen et al. (1998):

$$r_a = \frac{208}{u_2}, \tag{3}$$

where u_2 is the wind speed at the height 2 m.

Crop canopy resistance is (Allen et al., 1998):

$$r_c = \frac{r_l}{0.5LAI} = \frac{200}{LAI}, \tag{4}$$

where r_l is the daily average bulk stomata resistance of the well illuminated leaf (s m^{-1}) ($r_l \approx 100$ s m^{-1}), LAI is the active leaf area index.

Then, Penman-Monteith equation (Eq. (1)) with the above mentioned data for grass reference surface is (Allen et al.,1998):

$$ET_o = ET_r + ET_a = \frac{0.408\Delta(R_n - G)}{\Delta + \gamma(1 + 0.34u_2)} + \frac{\gamma \dfrac{900}{T + 273} u_2 (e_a - e_d)}{\Delta + \gamma(1 + 0.34u_2)}. \tag{5}$$

Penman-Monteith equation and modified calculation procedure (PM-BN)

The modification of Penman-Monteith equation and calculation procedure was re-developed using the same principle and equations like before by Penman (1948), but using newer information about boundary layer of the atmosphere (BLA) by Monin and Obukhov (1954). Continuous modifications were also published by Budagovskiy (1964), Novák (1989), Novák and Hurtalová (1987). The principle of „the big leaf" allows to calculate potential evapotranspiration based on the horizontal wet surface with zero canopy resistance $r_c = 0$. Eq. (6) was used to calculate ET_o in simulation models GLOBAL and model HYDRUS-ET (note – it differs from HYDRUS-1D) (Novák, 1995; Majerčák and Novák, 1992; Novák and Majerčák, 1992; Šimůnek et al., 1997):

$$ET_o = ET_r + ET_a = \frac{\phi(R - G)}{c_p + L\varphi} + \frac{\rho_a c_p D d'}{c_p + L\varphi}, \tag{6}$$

where ET_o is the potential evapotranspiration intensity (kg m^{-2} s^{-1}), R is net radiation at the evaporation surface level (W m^{-2}), G is the soil heat flux (W m^{-2}), ρ_a is the air density (kg m^{-3}), c_p is the moist air specific heat (J kg^{-1} K^{-1}) (c_p = 1005 J kg^{-1} K^{-1}), D is the velocity coefficient of turbulent transport (m s^{-1}), d' is the air saturation deficit, expressed as the difference of the specific humidity $d' = q_o - q$, q_o and q are specific air humidity of air saturated by water vapor and measured air humidity (kg kg^{-1}), L is the latent heat of vaporization (J kg^{-1}) ($L = 2.46\ 10^6$ J kg^{-1} at T = 20°), φ is the slope of vapor pressure curve.

The air saturation deficit $d' = q_o - q$ can be replaced by the saturation deficit $d = e_{2,o} - e_2$ using partial pressures $d' = 6.22 \times 10^{-4}\ d$ (kg kg^{-1}), T is the air temperature at 2-m height.

New knowledge of the BLA physics allowed to develop equation for the turbulent transport D calculation (Budagovskiy, 1964; Monin and Obukhov, 1954; Novák and Hurtalová, 1987). For neutral state of the atmosphere, equation for $D = 1/r_a$ can be written (Novák, 1995):

$$D = \frac{\kappa u_*}{\left(\dfrac{z_o u_*}{\nu_a}\right)^{0.5} + \ln\left(\dfrac{z_2 - d_e}{z_o}\right)}, \tag{7}$$

where u_* is the friction velocity (m s^{-1}), z_o is the roughness length of the evaporating surface (m), ν_a is the air kinematic viscosity (m s^{-1}).

RESULTS AND DISCUSSION

To compare quantitatively the results of reference canopy potential evapotranspiration (ET_o) performed by two modifications of Penman-Monteith equations (PM-FAO, PM-BN) the daily rates were calculated for the frost-free period from the 2nd of March to the 8th of December (later noted as a season) with standard meteorological characteristics and data from meteorological station Gabčíkovo for seasons of the 2000–2009 period.

ET_o seasonal totals of 10 years (2000–2009) calculated by the two described methods are presented in Fig. 1. Significant differences in results can be seen; the average seasonal ET_o difference is 217 mm of the water layer; the relative difference is 0.36. Minimum difference ET_o was calculated for year 2004 (24%) – 193 mm of the water layer – and maximum difference was in the year 2009 (31%) – 238 mm of the water layer.

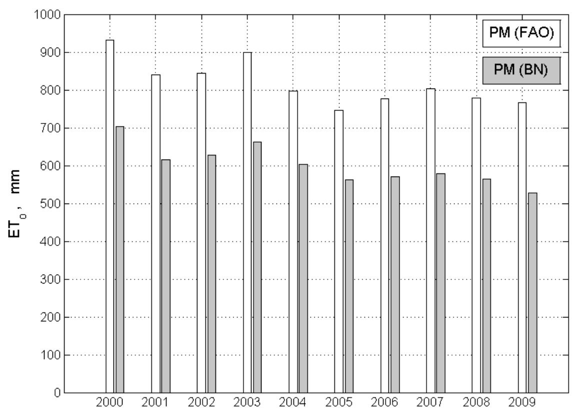

Fig. 1. Daily cumulative values ET_o, calculated according to the PM-FAO and PM-BN for the seasons of years 2000–2009. (Gabčíkovo, South Slovakia.)

What can be the reason of such differences? Fig. 2 presents cumulative potential evapotranspiration of the reference canopy calculated by both methods for season of the year 2009 (1, 2), as well as radiation ET_r (3, 4) and aerodynamic ET_a terms (5, 6) of Eqs (5) and (6). It can be seen, that the higher values of all the terms were calculated by the PM-FAO method in comparison to the PM-BN method. Net radiation R_n calculation method used in the PM-FAO procedure does not take into account the influence of different temperatures of evaporating (and radiating) surface upon the long-wave radiation intensity. It is calculated for the temperature measured at the standard height. It made the calculated difference in R_n for seasonal total of the year 2009 approx. 30%. As it can be seen from Eqs (5) and (6) radiation as well as aerodynamic terms of both equations are expressed in a different way. Radiation term of the PM-FAO method is indirectly proportional to the wind velocity. In the PM-BN modification it does not depend upon the wind velocity.

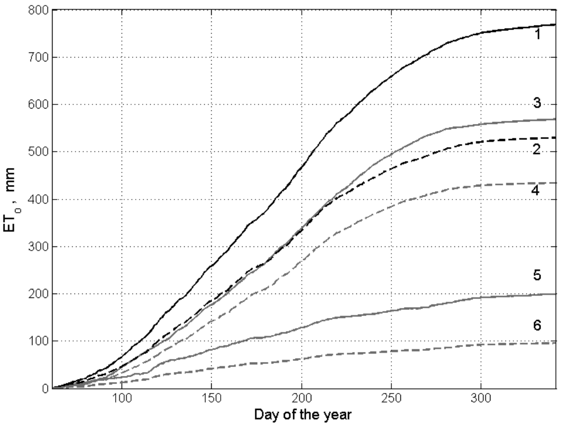

Fig. 2. Cumulative values of gross ET_o, radiation (ET_r) and aerodynamic element (ET_a) of the Eq. (5) according to the PM-FAO and PM-BN Eq. (6) method, for the season of the year 2009. (1) is ET_o, (PM-FAO), (2) is ET_o, (PM-BN); (3) is ET_r – (PM-FAO), (4) is ET_r – (PM-BN), (5) is ET_a, (PM-FAO), (6) is ET_a, (PM-BN). (Gabčíkovo, South Slovakia.)

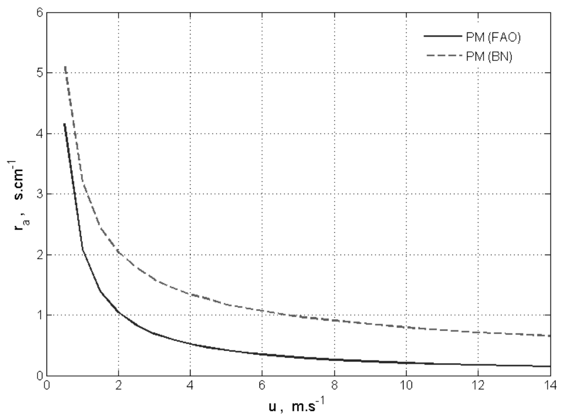

Fig. 3. Grass vegetation cover aerodynamic resistance r_a and wind velocity u, calculated by two various methods: in FAO modification by Eq. (3), in BN modification (inverse value of the Eq. (7)). (Gabčíkovo, South Slovakia.)

Aerodynamic resistances calculated by the Eqs (3) and (7) as a function of wind velocity u are in Fig. 3. The differences in resistances are about 100 percent at the most common wind velocities ($u = 2$ m s^{-1}) and are increasing with wind velocities. Aerodynamic resistances calculated in the framework of the PM-FAO procedure are smaller, which means higher aerodynamic term ET_a.

Finally, Fig. 4. presents correlation of the potential evapotranspiration daily values, calculated by both methods; the PM-BN is on horizontal axis. Correlation coefficient ($r = 0.97$) is high, RMSE = 0.88 mm and the average relative error (MRE) is 53%. This result confirms systematic differences between the both methods determination.

The reasons of such significant differences in daily totals of ET_o, calculated by the two methods can be attributed to several facts. Primarily to differences in the net radiation calculation methods. In principle, the both methods use the same method for the net radiation calculation (R_n), but there are differences in long-wave radiation balance calculation (R_{nl}). The PM-FAO method does not account for differences between the surface evaporation body temperature (T_s). As the temperature of the evaporating (radiating) surface the standard air temperature (T) at reference level is used, i.e. at the 2 m elevation. It is assumed that the both temperatures are the same. This will lead to the lower calculated net long-wave radiation R_{nl}, and to higher values of net radiation R_n. Modified PM-BN method accounts for the temperature difference $T_s - T$ on R_{nl} by an iteration process (Budagovskiy, 1964; Novák, 1987, 1995). Recently, Widmoser (2009) proposed iterative method to calculate surface temperature to increase the PM method accuracy too.

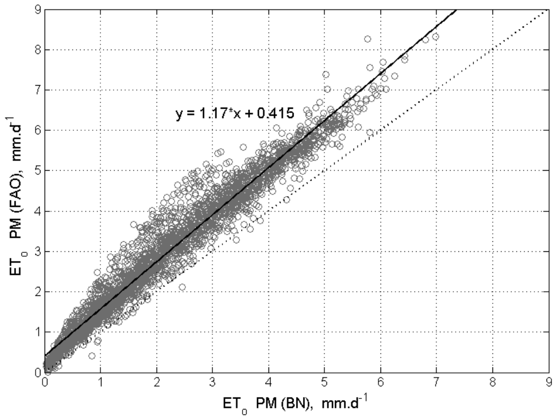

Fig. 4. Linear regression between ET_o calculated by PM-FAO and PM-BN, modification; as a reference method was chosen the modified Penman-Monteith BN. (Gabčíkovo, South Slovakia.)

Aerodynamic terms of the PM-FAO equation as well as that in the PM-BN are increasing with wind velocity. But that of the PM-FAO equation term is much higher. At the standard wind velocities, it is twice as high as that for PM-BN method, and thus the difference is increasing with the wind velocity. This is the result of different methods of r_a (or conductivity $D = 1/r_a$) calculation. An approximate method of r_a calculation (Eq. (2)) does not involve the resistance of the air layer (0, z_o), which is leading to the underestimated aerodynamic resistances and to higher values of the aerodynamic term. The PM-BN method is using Eq. (7) which involves into resistance the air layer (0, z) too.

Daily potential evapotranspiration rates of grass canopy ET_o, calculated for years 2000–2009, by the PM-FAO and the PM-BN methods (Fig. 4) exhibit a linear regression. Close correlation is the result of their common physical basis. The difference between results calculated by the same net radiation (to evaluate the sensitivity of both models to the aerodynamic term), was 12% (season of the year 2000) and 5% (season 2009). ET_o values calculated by the PM-FAO method were always higher.

Both methods were verified in a different way. The PM-FAO method was verified for different climate conditions on lysimeters data (Allen et al., 1989; Allen et al., 1998).

The PM-BN method was verified comparing calculated daily evapotranspiration rates with those, estimated and measured by the energy balance method at experimental field with maize canopy at Trnava (South Slovakia) by Novák and Hurtalová (1987). The same type of verification was performed within the NOPEX Project field campaign at Uppsala, Sweden for grass, spring barley, rice and winter wheat (Hurtalová et al., 1996; Novák et al., 1997).

Which method can be recommended? This question could be answered only, if verification of both methods would be implemented with the same models (HYDRUS and GLOBAL) data input sets, and the results compared with evapotranspiration real observation (determined by e.g. lysimeters), not by some other calculations. So far such verification has not been performed. This could be the subject of the future project within the Central European regional cooperation.

CONCLUSIONS

Results of potential evapotranspiration of reference grass canopy calculated by the two modifications of the Penman-Monteith equation application showed significant differences.

Higher values of ET_o were calculated by the PM-FAO method (Allen et al., 1998) for Gabčíkovo meteorological station, (average seasonal value 818 mm for seasons 2000–2009). Significantly lower (602 mm) values were calculated by the PM-BN method according to Novák (1989).

The reasons of these differences can be found in different methods of long-wave radiation evaluation and the aerodynamic resistance calculation. Long-wave radiation calculation method used in the PM-FAO method does not involve the evaporating (radiating) surface temperature of the radiating surface, but air temperature at standard height. Aerodynamic resistance is neglecting the resistance of the surface sublayer $(0, z_o)$.

The aim of this paper was not to prefer one method to the other, but to compare two methods of potential evapotranspiration calculation. In view of wide use of the both methods and also of the both mentioned numerical models, we tried to stress the possible results differences in their respective use. Also to point out the sources of such sometimes quite serious differences. Users should be aware of these at their use for scientific purposes, as well as, for practical applications (e.g. for irrigation water need forecasts).

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