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COMPUTATION OF ACTUAL EVAPOTRANSPIRATION ON VEGETATION-COVERED SOILS

OBLICZANIE EWAPOTRANSPIRACJI RZECZYWISTEJ NA GLEBACH POROŚNIĘTYCH ROŚLINNOŚCIĄ

Abstract

This paper discusses the concept of an algorithm designed to determine actual evapotranspiration, taking into account the type of vegetation covering the land, the purpose the land is used for, and varying weather and soil conditions. Simple calculation methods are applied, taking into account individual factors which have been considered separately in the studies of soil conditions published to date.

Keywords: *evapotranspiration*, *soil moisture retention*, *plant growth*, *sealing factor*

Streszczenie

Przedstawiono koncepcję algorytmu wyznaczania ewapotranspiracji rzeczywistej z uwzględnieniem rodzaju roślinności pokrywającej powierzchnię, sposobu użytkowania tej powierzchni, także dla różnych warunków pogodowych i glebowych. Zastosowane zostały proste metody obliczeń uwzględniające poszczególne czynniki prezentowane dotychczas odrębnie w opracowaniach na temat warunków glebowych.

Słowa kluczowe: *ewapotranspiracja*, *retencja wilgoci w glebie*, *wzrost roślin*, *współczynnik uszczelnienia*

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1. Introduction

Net precipitation is computed in order to determine how much precipitation can infiltrate further into the soil. A simplified model is used here, based on the Turc equation [4]. The following data is needed to use this model: the mean sun radiation (from astronomical tables), the mean local temperature, local precipitation and the type of vegetation (as required for an assessment of the evapotranspiration level). These items of data are readily available; a model based on them may then be used for further analysis in conjunction with an infiltration model that is necessary to assess the volume of water available for evapotranspiration. There is also the possibility of using the Penmann-Monteith evapotranspiration model [3] if complete data for this model can be collected (as required for the Turc equation plus earth surface mean albedo, cloud cover, water vapour pressure and wind speed).

Evapotranspiration in dry soils can be dramatically reduced when plants stop growing – the transpiration process can even be entirely halted. Dry soil types have good insulation properties (with regards to heat and vapour transfer) on their surface level; therefore, direct evaporation may be ignored here so that evapotranspiration is equal to transpiration (which, as stated above, may be close to zero). Actual evapotranspiration is calculated based on rhizosphere zone moisture, so the moisture characteristics must be known. The Corey-Brooks formula may be used in a simplified solution [1].

Net precipitation is therefore computed in the following way: potential evapotranspiration is determined based on actual precipitation data obtained from meteorological records; biota evapotranspiration is then assessed whilst taking into account the rhizosphere width, the dominant vegetation type, and the current vegetation season; finally, actual evapotranspiration is calculated (keeping the above remarks in mind).

2. Potential evapotranspiration

To exactly calculate potential evapotranspiration, a series of meteorological parameters must be determined which are measured in selected stations only. If those parameters are available, the full Penmann-Montheit model may be applied. If a radically simplified model is used, such as the Turc model, the results will represent only approximate values.

2.1. The Penmann equation [3]

$$\begin{aligned}v_p = \Bigg[& R_o(1-\alpha)\left(0.209-0.0.565\frac{n}{N}\right)- \\ & -\delta T^4(0.56-0.08e^{0.5})\left(0.10-0.90\frac{n}{N}\right)\Bigg]\left[R_o(1-\alpha)\left(0.209-0.565\frac{n}{N}\right)\right]-\frac{1}{59}\frac{\Delta}{\Delta+0.65}+ \\ & +0.26(e_n-e)(1-0.4v)\frac{0.65}{\Delta+0.65}\ [\mathrm{mm/d}]\end{aligned} \tag{1}$$

This equation includes the value of radiation at the boundary of the atmosphere R_o, albedo α, cloud cover n/N, temperature T, the Stefan-Boltzmann constant δ [cal×cm^2/d/K], water vapour pressure e [hPa], saturated water vapour pressure e_n [hPa] [5], the gradient of saturated water vapour pressure Δ [hPa/K] at a mean air temperature, the wind speed v at the height of 10 m.

2.2. The Turc equation [3]

$$v_p = 0.15 \frac{T}{T+15}(R_n + 50) \tag{2}$$

where:

v_p – mean rate of potential evapotranspiration [mm/10 days];
T – mean monthly temperature [°C];
R_n – net radiation [cal/cm^2/d], corresponding to 2.064 R_n [W/m^2].

The value of net radiation is calculated from the Feddes equation, based on the radiation value at ground level:

$$R_n = 0.649 R_z - 23 \tag{3}$$

R_z – radiation at ground level (from the Kimball equation):

$$R_z = (0.25 - 0.5n/N)R_o \tag{4}$$

R_o – radiation at the boudnary of the atmosphere – from astronomical tables.

Kowalik also provides the formulae used to calculate the last mentioned value for individual days of the year.

The value for daily evapotranspiration can be assessed as a portion of monthly evapotranspiration using the formula for the monthly mean and assuming 10.15 days as average one third of a month:

$$R_n \text{ [mm/d]} = R_n \text{ [mm/10 days]}/10.15.$$

3. Actual evapotranspiration

3.1. The effect of vegetation

The value of actual evapotranspiration v_e is determined using a correction factor for plant growth intensity:

$$v_e = \kappa v_p \tag{5}$$

$\kappa(t)$ is a biological coefficient depending on the ecosystem (crop type) and growth phase; for wheat $\kappa = 1$ [4]. The following general growth timeline may be adopted for natural plant biocenoses:

1 March – 20 April – $\kappa = 0.44$

21 April – 20 June – $\kappa = 0.44$ to 1.08, i.e.:

$$\kappa = 1.08 - (1.08 - 0.44) \times (78\,[\mathrm{d}] - t) / 78\,[\mathrm{d}] \tag{6}$$

21 June – 2 September – $\kappa = 1.08$

3 September – 31 October – κ= 1.08 to 0.58, i.e.:

$$\kappa = 0.58 + (1.08 - 0.58) \times (304\,[\mathrm{d}] - t) / 58\,[\mathrm{d}] \tag{7}$$

1 November – 20 December – $\kappa = 0.58$ to 0.00, i.e.:

$$\kappa = 0.58 \times (365\,[\mathrm{d}] - t) / 61\,[\mathrm{d}] \tag{8}$$

1 January – 28 February – $\kappa = 0.00$ to 0.44, i.e.:

$$\kappa = 0.44 \times t / 59\,[\mathrm{d}] \tag{9}$$

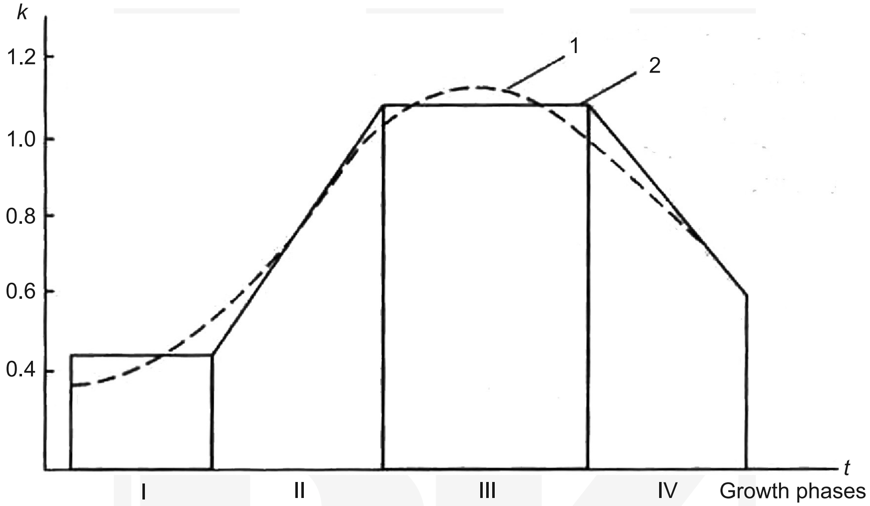

Fig. 1. The biological coefficient in the several phases of plant growth [4]

3.2. Evapotranspiration during precipitation

The atmosphere is completely saturated with moisture during precipitation; therefore, evapotranspiration cease. However, in practice, either data on mean daily or 6-hour precipitation are used. In fact, the rain does not fall for the entire defined period, but short episodes of rainfalls are separated by shorter or longer intervals without precipitation. Moisture deposited on the ground surface or on plants is than available to an extent determined by the intensity of the rain. In these conditions, the evapotranspiration rate may be defined as equal to potential evapotranspiration up to the value of precipitation intensity v_r; and above this limit, to the higher of the two values: precipitation intensity or actual evapotranspiration calculated for a dry (precipitation-free) period:

$$v_e' = \max(\min[v_p; v_r]; v_e). \tag{10}$$

3.3. Limitation of evapotranspiration in dried soils

A reduction in the growth and consequently in the transpiration of plants occurs for pF = 2.85 (Fig. 2.), i.e. for suction head $h_s = 7$ m. The beginning of dramatic reduction in plant growth, which may be associated with transpiration level $v_e = 80\%$ of the potential value, corresponds to pF = 3.2, or $h_s = 16$ m. A complete halt in plant growth (a reduction of v_e to 1%) corresponds to pF = 3.7, or $h_s = 50$ m. Finally, the permanent wilting point, entailing a complete failure of transpiration, corresponds to pF = 4.2, or $h_s = 160$ m [3]. As stated above, direct evaporation from the ground surface may be ignored in these circumstances. Consequently, evapotranspiration is equivalent to transpiration.

The model requires that the actual evapotranspiration rate be determined on the basis of moisture in the subsurface soil layer – the so called rhizosphere. This in turn requires that the retention curve $\theta(h_s)$ be determined for the drying process, taking into account residual moisture left in soil as a result of hysteresis. Using the simplest formula describing this characteristic, the Corey-Brooks equation, the moisture values are calculated as follows:

$$\theta = (\theta_n - \theta_b)\left(\frac{h_k}{h_s}\right)^{m_\theta} - \theta_b, \tag{11}$$

where:

$$m_\theta = \frac{2}{m_k - 2},$$

θ_n – moisture at full saturation, which during the drying process is equal to porosity n,
θ_b – residual moisture with adhesive nature during the drying process,
h_s – suction head [m],
h_k – capillary rise height.

The value of residual moisture is determined using the capillary bundle model [2] as follows:

$$\theta_b = 0.163\,[\mathrm{m}^{-1/2}]\, n\sqrt{h_{\min}}\,\sqrt[3]{\frac{1-n}{n}}\,\sqrt[6]{\frac{h_{\min}}{h_s}}. \tag{12}$$

The value of $h_{\min}$ is close to the value of h_k, and is calculated more precisely using the formula:

$$h_{\min} = 6.05\cdot 10^{-6}\,[\mathrm{m}]\frac{1-n}{n}\frac{\alpha}{d_A}, \tag{13}$$

where the parameter $\alpha = d_s/V_s$ means the coefficient of grain shape ($\alpha \cong 10$, for spherical grains $\alpha = 6$), and d_A represents the equivalent spherical diameter for an equivalent grain surface A_s. The value of suction lift h_s may be regarded as corresponding to the wilting point, i.e. equal to 160 m.

Four threshold values of moisture are determined using these parameters for the soil type: the moisture value at the beginning of growth reduction – θ_p; the moisture value causing a dramatic growth reduction – θ_e; the moisture value causing a complete halt of plant

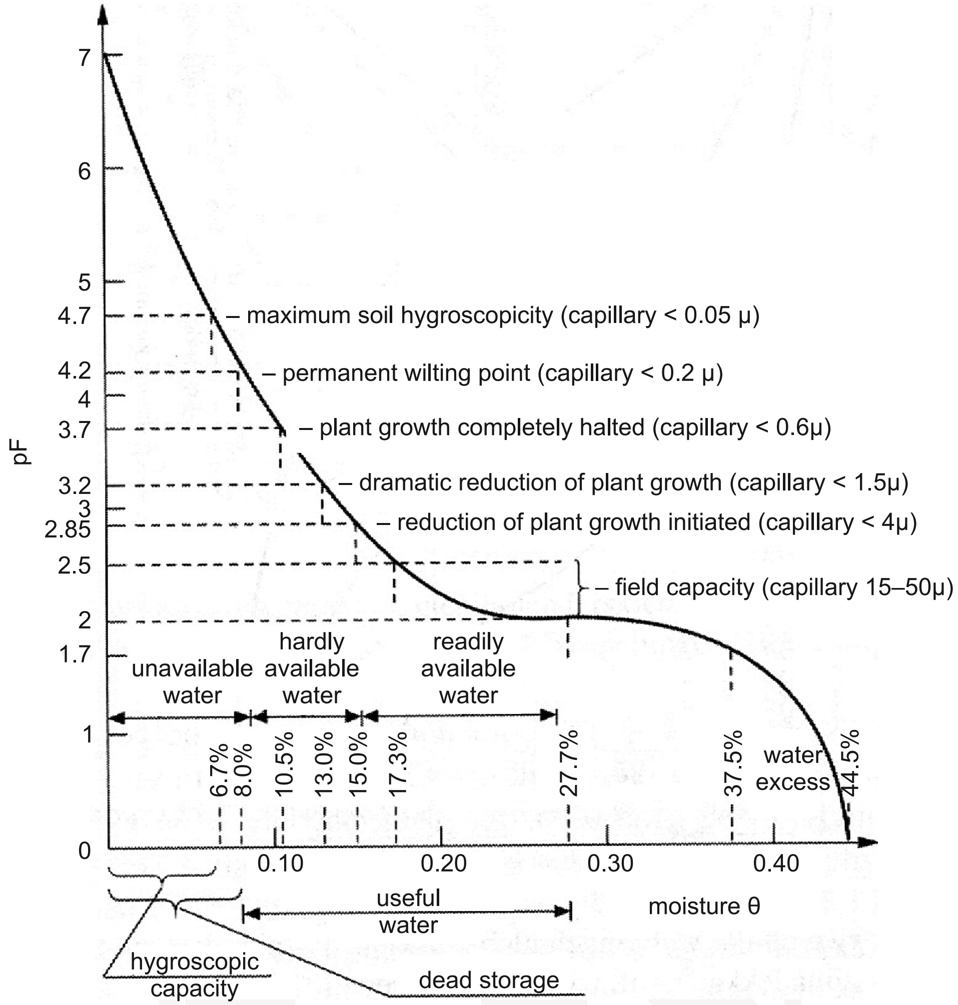

Fig. 2. Soil moisture retention curve on a logarithmic scale pF with major water capacity values for arable black soil [3]

growth – θ_f; the moisture value causing permanent wilting – θ_t. The following formula is used to calculate evapotranspiration from dry soil (5): $v'_e = \kappa(\theta) v_e$, where $\kappa(\theta)$ is the coefficient reducing actual evapotranspiration. The coefficient is determined for individual intervals of the moisture value using the following formulae:

$$\theta \geq \theta_p : \qquad \kappa(\theta) = 1,$$

$$\theta_p > \theta \geq \theta_e : \qquad \kappa(\theta) = 0.2 \frac{\theta - \theta_e}{\theta_p - \theta_e} + 0.8, \tag{14}$$

$$\theta_e > \theta \geq \theta_f : \qquad \kappa(\theta) = 0.79\frac{\theta - \theta_f}{\theta_e - \theta_f} + 0.01, \tag{15}$$

$$\theta_f > \theta \geq \theta_t : \qquad \kappa(\theta) = 0.01\frac{\theta - \theta_t}{\theta_f - \theta_t}, \tag{16}$$

$$\theta < \theta_t : \qquad \kappa(\theta) = 0.$$

4. Land use

The vegetation cover changes with land development or type of use – this affects the value and variations in time of the biological coefficient $\kappa(t)$. In addition, the problem of land surface sealing and soil drainage appears in the areas of compact building development. Regardless of the problems of irrigation and drainage that are associated with the filtration process in the saturation zone and are not covered by this study, the surface sealing degree may be simply expressed using the ICF sealing factor known from the literature on the subject (Tab. 1). Approximately (i.e. ignoring the method and degree of drainage), it may be assumed that not only does infiltration into the soil become reduce, so does evapotranspiration from the soil. Therefore, depending on the flow direction, a reduction is observed either in the surface infiltration rate (not the precipitation intensity) or in the actual evapotranspiration value. The actual sealing factor in an area is determined as a weighted arithmetic mean based on the detailed balance of land use.

Table 1

Examples of degrees [%] of surface sealing in a river basin

The category (type) of land development (according to the Polish classification of spatial development)	
Type of land use	ICF [%]
Green area – pasture land, forest, agricultural land (ZN, ZL, R)	0.5
Farm building area (MR, MRN)	60
Intensive farming area (RU, RPO)	10–20
Detached houses (MN)	40–70
Housing and service area (MU)	50–75
Industrial area (P)	60–75
Tourist service and skiing area (US)	5
Technical infrastructure area (IT)	70

5. Conclusions

The proposed model used to compute actual evapotranspiration combines and supplements the known concepts of calculating effects exercised by individual basic factors with necessary details. The discussed algorithm facilitates computations without the need to acquire non-standard or not readily available data. Only the calculations of evaporation from dried soils require that the value of moisture in the rhizosphere be determined. This parameter is assessed using models of infiltration in the vadose zone, with various degrees of complexity. However, this problem exceeds the scope of the topics covered by this paper.

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