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Evapotranspiration of Grasslands and Pastures in North-Eastern Part of Poland

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1. Introduction

The problem of plant water requirements and supply is of great importance to agricultural water management. It is crucial to determine and provide the water amount required in a certain region to support the plants assimilation function. The quantity of water required on a specific farm can be determined by analyzing the water balance, where precipitation and evapotranspiration are basic elements. Evapotranspiration data is also indispensable when mathematically modelling the water balance. The values of evapotranspiration can be obtained from lysimeter measurements. However, this measurement is labour intensive and also requires special equipment; thus, it is not widely applied. To address this problem, a number of methods of evapotranspiration estimation based on physical and empirical equations are available, where the quantity of evapotranspiration depends on other measured factors. Penman (1948) developed a method for determination of the potential evapotranspiration as a product of the crop coefficient for a certain crop in a certain development stage and the reference evapotranspiration (Łabędzki et al., 1996). Open water surface evaporation is the reference evapotranspiration used in this method. Currently, the method most widely applied in Poland for evapotranspiration estimation is a method called the “French Modified Penman method”, which is a version of FAO Modified Penman method (Doorenbos & Pruitt, 1977), with the net radiation flux calculated by Podogrodzki (Roguski et al., 1988). Name of “Modified Penman method” is using in further part of this text. On the other hand, the Food and Agriculture Organization (FAO) recommends the Penman-Monteith method for evapotranspiration estimation (Allen et al., 1998). The aforementioned methods require relevant crop coefficients to estimate the potential evapotranspiration. Although crop coefficients for grasslands and pastures applicable to the modified Penman are available for Polish conditions (Roguski et al., 1988; Brandyk et al., 1996; Szuniewicz & Chrzanowski, 1996), the problem occurs when the potential evapotranspiration has to be calculated according to the FAO standards which require the Penman-Monteith method to be used. Both the methods (Modified Penman and Penman-Monteith) require meteorological data including: air temperature, humidity, cloudiness or sunshine and wind speed. If one or more of the required inputs are not available, then applying any of the two methods is difficult, perhaps even impossible. In such cases, the Thornthwaite method, developed in 1931, can be a viable alternative (Byczkowski, 1979; Skaags, 1980; Newman, 1981; Pereira & Pruitt, 2004). The Thornthwaite method is commonly used in the USA. This method requires only two basic climatic inputs that

determine the solar energy supply and are necessary to estimate the potential evapotranspiration: air temperature and day length.

There are two objectives of this chapter. The first objective is to determine the crop coefficient needed when estimating the potential evapotranspiration with the Penman-Monteith method. The second objective is a comparative analysis of the potential evapotranspiration estimates obtained from the Thornthwaite method and the crop coefficient approach with Penman-type formula as a reference evapotranspiration.

2. Reviewing the selected methods for evapotranspiration estimation: Modified Penman, Penman-Monteith and Thornthwaite

It can be assumed, that the amount of a farm plants evapotranspiration depends on such factors as atmosphere condition, plants development stage and soil moisture. The interdependence of these factors is complex and difficult to describe mathematically. This dependence can be expressed as a product of following functions:

$$ET = f_1(M) \cdot f_2(P) \cdot f_3(S) \quad (1)$$

where:

M – atmosphere factors,

P – plant factors,

S – soil moisture factors.

Groups of atmosphere factors can be formulated as a reference evapotranspiration (ET_0), which characterises meteorological conditions in the evapotranspiration process and describes evaporation ability in the atmosphere. This factor determines the intensity of evapotranspiration process in the case of unlimited access to a water source, that is deplete of soil water:

$$f_1(M) = ET_0 \quad (2)$$

$f_2(P)$ function describes the influence of plant parameters such as: plant species, development stage, mass of above ground and underground parts, leaf area index (LAI), growth dynamics, nutrients supply, yield and frequency of harvesting. A group of these parameters is expressed as a crop coefficient (k_c), which is empirically determined independently by soil moisture conditions:

$$f_2(P) = k_c \quad (3)$$

$f_3(S)$ function describes the influence of soil moisture and the availability of soil water for plants (as a soil water potential) on evapotranspiration amount. With our knowledge of soil physics and plant physiology knowledge, it can be assumed that evapotranspiration during sufficient water supply does not depend or slightly depend on soil moisture (Łabędzki et al., 1996, as cited in: Kowalik, 1973; Salisbury & Ross, 1975; Feddes et al., 1978; Rewut, 1980; Olszta, 1981; Korohoda, 1985; Więckowski, 1985; Brandyk, 1990). Sufficient water supply does not limit evapotranspiration and plant yield is defined as a soil moisture range between optimum water content (when air content equals at least 8 – 10% in root zone) and refill point (pF 2.7 – 3.0). In other words, sufficient water supply means easily available water or readily available water (RAW). Evapotranspiration reductions has a place, when

RAW becomes consumed by plants. The deciding factor of evapotranspiration reduction amounts is the difference between actual soil moisture content and soil moisture content when the evapotranspiration process fades (wilting point). Thus, it can be showed in general (Łabędzki et al., 1996, as cited in: Olszta et al., 1990; Łabędzki & Kasperska, 1994; Łabędzki, 1995):

$$f_3(S) = k_s(\theta) \quad (4)$$

where:

$k_s(\theta)$ – soil coefficient as a function of soil moisture.

Summarizing, equation (1) can be noted as below, where ET_a is called actual evapotranspiration:

$$ET_a = ET_0 \cdot k_c \cdot k_s \quad (5)$$

In cases when sufficient water supply does not limiting evapotranspiration ($k_s = 1$), actual evapotranspiration (ET_a) equals potential evapotranspiration (ET_p):

$$ET_p = ET_0 \cdot k_c \quad (6)$$

The problem becomes how to determine a reference evapotranspiration and a crop coefficient.

2.1 The reference evapotranspiration computing by the Modified Penman method

Penman (1948) estimated the evaporation from an open water surface, and than used that as a reference evaporation. This method requires measured climatic data on temperature, humidity, solar radiation and wind speed. Analyzing a range of lysimeter data worldwide, Doorenbos and Pruitt (1977) proposed the FAO Modified Penman method. These authors adopted the same approach as Penman to estimate reference evapotranspiration. They replaced Penman's open water evaporation with evapotranspiration from a reference crop. The reference crop was defined as "an extended surface of an 8 to 15 cm tall green grass cover of uniform height, actively growing, completely shading the ground, and not short of water". The reference evapotranspiration according to Modified Penman method commonly applied in Poland was calculated by the following algorithm. This algorithm was developed according to following literature: Roguski et al. (1988); Feddes & Lenselink (1994), Kowalik (1995), Kędziora (1999), Woś (1995), Łabędzki et al. (1996), Łabędzki (1997), Feddes et al. (1997) and van Dam et al. (1997). The parameters are as follows:

ϕ - latitude of meteorological station [$^\circ$],

J - day number [-],

T - daily average air temperature [$^\circ\text{C}$],

RH - daily average relative humidity [%],

h_i - anemometer level above ground level [m],

v_{hi} - average wind speed on 10 m level [m s^{-1}],

c - average daily cloudiness in 11 degree scale,

n - duration of direct sunshine [h],

R_a - solar radiation at the external atmosphere border [W m^{-2}],

α - albedo, in case of a crop equals to 0.23 [-],

γ - the psychrometric constant equals to 0.0655 [kPa K^{-1}],

λ - latent heat of vaporization equals to 2.45 [MJ kg⁻¹],

σ - Stefan – Boltzmann constant equals to 4.903*10⁻⁹ [MJ m⁻² K⁻⁴ d⁻¹],

G_{sc} – solar constant equals to 0.082 [MJ m⁻² min⁻¹].

Saturation vapour pressure (e_d) [kPa]:

$$e_d = 0.6108 \cdot \exp\left(\frac{17.27 \cdot T}{T + 237.3}\right) \quad (7)$$

Actual vapour pressure (e_a) [kPa]:

$$e_a = \frac{RH}{100} \cdot e_d \quad (8)$$

The slope of the vapour pressure curve (Δ) [kPa °C⁻¹]:

$$\Delta = \frac{4098 \cdot e_d}{(T + 237.3)^2} \quad (9)$$

Wind speed on 10 m level above ground level (v_{10}) [m s⁻¹]:

$$v_{10} = \frac{v_{hi}}{\left(\frac{h_i}{10}\right)^{1/7}} \quad (10)$$

Solar declinations (δ) [rad]:

$$\delta = 0.409 \cdot \sin\left(\frac{2\pi}{365} \cdot J - 1.39\right) \quad (11)$$

Relative distance to the Sun (d_r) [-]:

$$d_r = 1 + 0.033 \cdot \cos\left(\frac{2\pi}{365} \cdot J\right) \quad (12)$$

Time from sunrise to noon (w_s) [rad]:

$$w_s = a \cos(-\tan \varphi \cdot \tan \delta) \quad (13)$$

Possible sunshine (N) [h]:

$$N = \frac{24}{\pi} \cdot w_s \quad (14)$$

Solar radiation at the external atmosphere border (R_a) [W m⁻²]:

$$R_a = \frac{24 \cdot 60}{\pi} \cdot G_{sc} \cdot d_r \cdot (w_s \cdot \sin \varphi \cdot \sin \delta + \cos \varphi \cdot \cos \delta \cdot \sin w_s) \quad (15)$$

Relation between real radiation to possible radiation – in case when sunshine value is not available there is calculated according to Angström criteria:

$$\frac{n}{N} = 1 - \frac{c}{10} \quad (16)$$

The net incoming short wave radiation flux (R_{ns}) [$W\ m^{-2}$]:

$$R_{ns} = R_a \cdot (1 - \alpha) \cdot \left(0.209 + 0.565 \cdot \frac{n}{N} \right) \quad (17)$$

The net outgoing long wave radiation flux (R_{nl}) [$W\ m^{-2}$]:

$$R_{nl} = \sigma \cdot (T + 273.2)^4 \cdot (0.56 - 0.08 \cdot \sqrt{10 \cdot e_a}) \cdot \left(0.1 + 0.9 \cdot \frac{n}{N} \right) \quad (18)$$

The net radiation flux (R_n) [$W\ m^{-2}$]:

$$R_n = R_{ns} - R_{nl} \quad (19)$$

The aerodynamic factor (E_a) [$mm\ d^{-1}$]:

$$E_a = 2.6 \cdot (e_d - e_a) \cdot (1 + 0.4 \cdot v_{10}) \quad (20)$$

Modified Penman reference evapotranspiration (ET_{MP}) [$mm\ d^{-1}$]:

$$ET_{MP} = \frac{\Delta}{\gamma + \Delta} \cdot \frac{R_n}{\lambda} + \frac{\gamma}{\gamma + \Delta} \cdot E_a \quad (21)$$

2.2 The reference evapotranspiration computing by the Penman-Monteith method

Among scientists is unanimous the consensus is that the best method of evapotranspiration calculation is a method proposed and developed by John Monteith (1965). Monteith's derivation was built upon that of Penman (1948) in the now well-known combination equation (combination of an energy balance and an aerodynamic formula). The equation describes the evapotranspiration from a dry, extensive, horizontally uniform vegetated surface, which is optimally supplied with water. This equation is known as the Penman-Monteith equation and it is currently recommending by FAO. Potential and even actual evapotranspiration estimates are possible with the Penman-Monteith equation, through the introduction of canopy and air resistance to water vapour diffusion. Nevertheless, since accepted canopy and air resistance may not be available for many crops, a two-step approach is still recommended under field conditions. The first step is the calculation of the reference evapotranspiration as an evapotranspiration of a reference crop for some steady parameters and soil moisture conditions. In the second step the actual evapotranspiration is calculated using the root water uptake reduction due to water stress. The reference crop is defined as "a hypothetical crop which is grass, with a constant, uniform canopy 12 cm tall, constant canopy resistance equals to $70\ s\ m^{-1}$, constant albedo equals to 0.23, in conditions of active development and optimally supplied with water" (Łabędzki et al., 1996; Feddes et al., 1997; van Dam et al., 1997; Allen et al., 1998; Howell & Evett, 2004, as cited in: Monteith, 1965). The Penman-Monteith reference evapotranspiration recommended by FAO was calculated by a similar algorithm shown in point 2.1. The difference between the Modified Penman and Penman-Monteith methods bases on solar radiation and an aerodynamic

formula calculation in general. Named factors were calculated according to following formulas shown below (Feddes & Lenselink, 1994).

The following parameters were used:

H- altitude of meteorological station over sea level [m],

T_{Kmin} – daily minimum air temperature [K],

T_{Kmax} – daily maximum air temperature [K],

v – average wind speed on 2 m level [$m\ s^{-1}$],

σ - Stefan – Boltzmann constant equals to $5.6745 \cdot 10^{-8}$ [$W\ m^{-2}\ K^{-4}$],

Solar radiation at the external atmosphere border (R_a) [$W\ m^{-2}$]:

$$R_a = 435 \cdot d_r \cdot (w_s \cdot \sin \varphi \cdot \sin \delta + \cos \varphi \cdot \cos \delta \cdot \sin w_s) \quad (22)$$

Solar radiation (R_s) [$W\ m^{-2}$]:

$$R_s = R_a \cdot \left[0.25 + \left(0.5 \cdot \frac{n}{N} \right) \right] \quad (23)$$

The net incoming short wave radiation flux (R_{ns}) [$W\ m^{-2}$]:

$$R_{ns} = (1 - \alpha) \cdot R_s \quad (24)$$

The net outgoing long wave radiation flux (R_{nl}) [$W\ m^{-2}$]:

$$R_{nl} = \left(0.9 \cdot \frac{n}{N} + 0.1 \right) \cdot (0.34 - 0.139 \cdot \sqrt{e_a}) \cdot \sigma \cdot \frac{(T_{Kmax}^4 + T_{Kmin}^4)}{2} \quad (25)$$

The radiation factor (R_n') [$mm\ d^{-1}$]:

$$R_n' = 86400 \cdot \frac{(R_{ns} - R_{nl})}{\lambda} \quad (26)$$

The atmospheric pressure [p_a] [kPa]:

$$p_a = 101.3 \cdot \frac{(T + 273.16 - 0.0065 \cdot H)}{T + 273.16} \quad (27)$$

The psychrometric constant (γ) [kPa $^{\circ}C$]:

$$\gamma = 1615 \cdot \frac{p_a}{\lambda} \quad (28)$$

Modified psychrometric constant (γ') [kPa $^{\circ}C$]:

$$\gamma' = (1 + 0.337 \cdot v) \cdot \gamma \quad (29)$$

The aerodynamic factor (E_a) [$mm\ d^{-1}$]:

$$E_a = \frac{900}{(T + 275)} \cdot v \cdot (e_d - e_a) \quad (30)$$

And finally Penman-Monteith reference evapotranspiration (ET_{P-M}) [mm d⁻¹]:

$$ET_{P-M} = \frac{\Delta}{\Delta + \gamma} \cdot R_n' + \frac{\gamma}{\Delta + \gamma} \cdot E_a$$

(31)

2.3 Crop coefficient

Potential evapotranspiration is calculated by multiplying ET_o by k_c , a coefficient expressing the difference in evapotranspiration between the cropped and reference grass surface. The difference can be combined into a single coefficient, or it can be split into two factors describing separately the differences in evaporation and transpiration between both surfaces. The selection of the approach depends on the purpose of the calculation, the accuracy required, the climatic data available and the time step with which the calculations are executed (Allen et al., 1998). Due to the purpose of this chapter, only the single coefficient approach is taken under consideration. The single crop coefficient combined the effect of crop transpiration and soil evaporation. The crop coefficient expresses crop actual mass and development stage influence on the evapotranspiration value, in sufficient soil moisture content. It is dependant on crop type, development stage and yield. The generalized crop coefficient curve is shown in Figure 1. Shortly after the planting of annuals or shortly after the initiation of new leaves for perennials, the value for k_c is small, often less than 0.4. The k_c begins to increase from the initial k_c value, $k_{c\,ini}$, at the beginning of rapid plant development and reaches a maximum value, $k_{c\,mid}$, at the time of maximum or near maximum plant development. During the late season period, as leaves begin to age and senesce due to natural or cultural practices, the k_c begins to decrease until it reaches a lower value at the end of the growing period equal to $k_{c\,end}$ (Roguski et al., 1988; Allen et al., 1998).

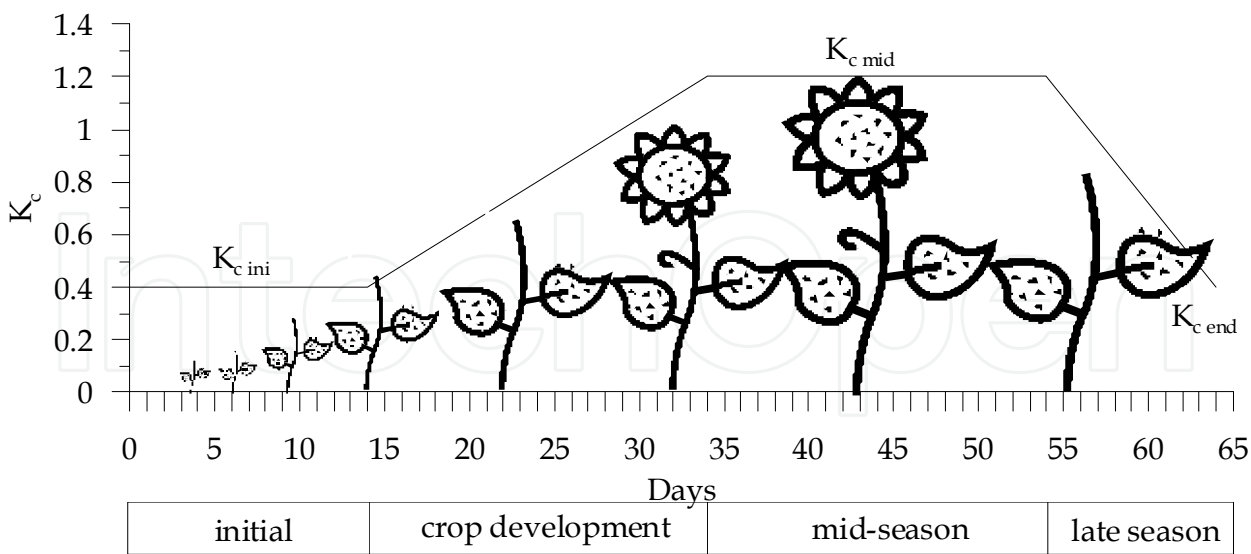


Fig. 1. Crop coefficient due to plant development stage

The objective of this work is to determine the crop coefficient needed when estimating the potential evapotranspiration with the Penman-Monteith method, when the potential evapotranspiration calculated as a product of Modified Penman reference evapotranspiration and appropriate crop coefficient for this method is known. Based on

procedures proposed by Feddes et al. (1997), the conversion of the Modified Penman crop coefficient k_{cMP} to the Penman-Monteith crop coefficient k_{cP-M} can be write as:

$$ET_p = ET_{MP} \cdot k_{cMP} = ET_{P-M} \cdot k_{cP-M} \quad (32)$$

from which:

$$k_{cP-M} = \frac{ET_{MP} \cdot k_{cMP}}{ET_{P-M}} \quad (33)$$

2.4 Potential evapotranspiration estimation by the Thornthwaite method

Both Modified Penman and Penman-Monteith methods required many climatic inputs like: air temperature, relative humidity, wind speed and solar radiation or at least daily sunshine. These are limited or even not available for many regions. Another problem is noncontinuous data series for some periods. Thus using the Modified Penman and Penman-Monteith methods for evapotranspiration calculation is not so easy and problematic in some cases. An alternative commonly used in the United States is the Thornthwaite method, because it requires only air temperature as a input data (Skaags, 1980; Newman, 1981). This method is based on determination of available energy required for the evaporation process. The relationship between average monthly air temperature and potential evapotranspiration is calculated based on a standard 30 days month with 12 hours of daylight each day according to the following equation (Byczkowski, 1979; Newman, 1981; Pereira & Pruitt, 2004):

$$ET_{pT} = 16.2 \cdot \left(\frac{10 \cdot T_j}{I} \right)^a \quad (34)$$

where:

ET_{pT} – Thornthwaite monthly potential evapotranspiration (mm),

d_f – correction factor for daylight hours and days in month (-),

T_j – average monthly air temperature ($^{\circ}\text{C}$),

I – annual heat index as a sum of monthly heat index I_i :

$$I = \sum_{i=1}^{12} I_i = \sum_{i=1}^{12} \left(\frac{T_i}{5} \right)^{1.514} \quad (35)$$

a – coefficient derived from climatological data:

$$a = 6.75 \cdot 10^{-7} \cdot I^3 - 7.71 \cdot 10^{-5} \cdot I^2 + 1.79 \cdot 10^{-2} \cdot I + 0.492 \quad (36)$$

In order to convert the estimates from a standard monthly ET_{pT} to a decade of evapotranspiration the following correction factor for daylight hours and days in month d_f (-) was used:

$$d_f = \frac{N_{dec}}{360} \quad (37)$$

where:

N_{dec} - possible sunshine for decade (h)

It must to be noted, that the Thornthwaite method is valid for average monthly air temperature from 0 to 26.5 °C.

3. Grasslands and pastures in the north-eastern part of Poland and local condition climate data

As Statistical Yearbook of Agriculture and Rural Areas (2009) presents, grasslands and pastures occupy about 3271.2 thousand hectares which is 20% of the total agricultural land in Poland. According to administrative division, the north-eastern part of Poland are Podlaskie and the eastern part of Warmińsko-Mazurskie voivodships. Grasslands and pastures occupy 393.5 thousand hectares (35%) and 290 thousand hectares (28.1%) of these voivodships agricultural land respectively. The valley of the River Biebrza, (22° 30'–23° 60' E and 53° 30'–53° 75' N) (Fig. 2) is one of the last extensive undrained valley mires in Central Europe. The Biebrza features several types of mires. The dominant types are fens, which account for some 75.9% of the wetland area (Okruszko, 1990). The altitude of the valley ranges from 100 to 130 m above mean sea level and the catchment area of approximately 7000 km² has a maximum altitude of 160 m (Byczkowski & Kicinski, 1984). The mean yearly rainfall is 583 mm, of which 244 mm falls in the wet summers. Mean annual temperature is rather low (6.8 °C), and the growing season is quite short (around 200 days) (Kossowska-Cezak, 1984). The part of Warmińsko-Mazurskie voivodship is Warmia region. Main town (former capital of Warmia region) situated on the north part of Warmia region (Fig. 2) is Lidzbark Warmiński (20° 35' E, 54° 08' N).



Fig. 2. An approximate location of considered regions in Poland

The altitude of the region ranges from 80 to 100 m above mean sea level on the borders and falls down from 40 to 50 m above mean sea level to the center. Brown Soils and Mollic Gleysols developed from silt and clay dominate in this. These soils are situated on sloping

areas with partly well surface water outflow. In the study region average yearly air temperature is equal to 7.1°C and average yearly sum of precipitation equal to 624 mm. The highest amount of rainfall is usually observed in July and August. The vegetation period lasts about 200 days. The snow cover occurs during 60–65 days (Nowicka et al., 1994). The needed meteorological data are available for the 1989-2004 grassland growing seasons derived from the Biebrza meteorological station located in the Middle Biebrza River Basin. The estimation of the pasture evapotranspiration will be based on the meteorological data collected in the Warmia region during the 1999 through 2010 period.

4. Results and discussion

The decade Modified Penman and Penman-Monteith reference evapotranspiration values were calculated both for Warmia Region and Middle Biebrza River Basin. The relationship between reference evapotranspiration values of two kinds of Penman methods was shown on Fig. 3.

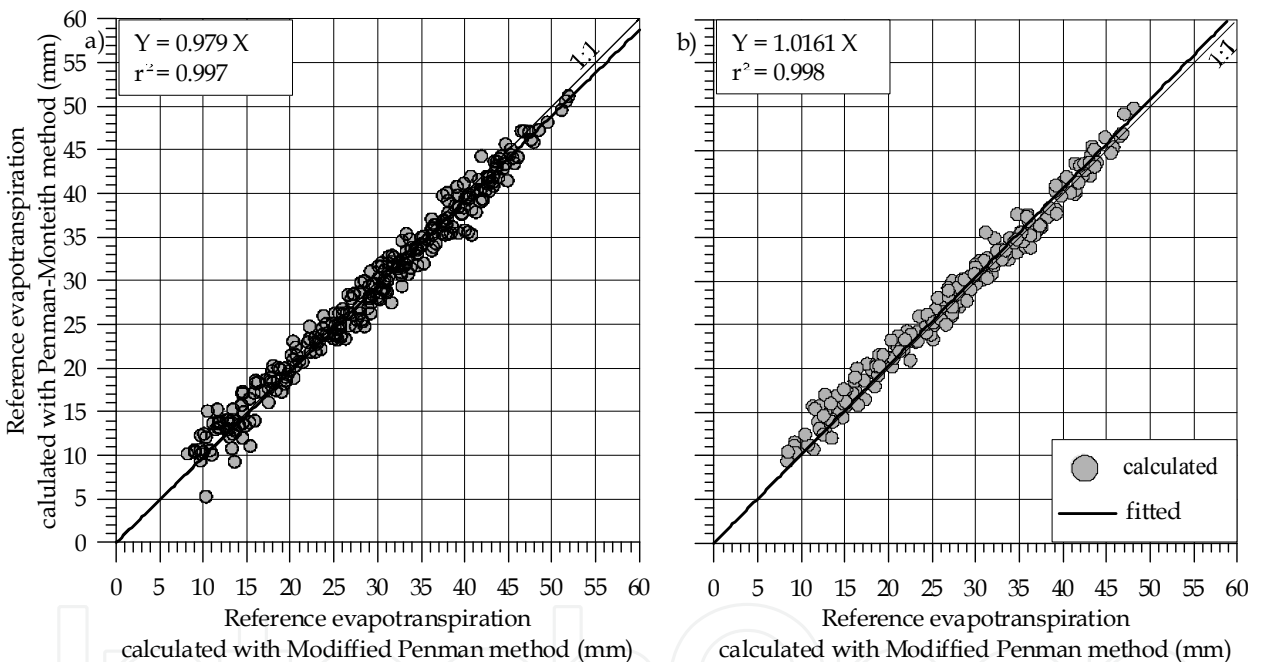


Fig. 3. The relationship between the Modified Penman and the Penman-Monteith reference evapotranspiration for: a) Middle Biebrza River Basin, b) Warmia Region

The relationship was fitted by linear regression through origin. Obtained linear equations indicates there is not significant difference between reference evapotranspiration calculated with Modified Penman and Penman-Monteith methods in both cases. It must to be noted that there is very good correlation between Modified Penman and Penman-Monteith methods. The coefficient of determination r^2 is equal to 99.7% and 99.8% respectively. Due to linear equation, Penman-Monteith reference evapotranspiration values are about 2% lower than values calculated by Modified Penman method for Middle Biebrza River Basin case (Fig. 3a). Whereas, an opposite situation was observed for Warmia Region. Reference evapotranspiration values calculated by the Modified Penman are 1.6% lower than values obtained by the Penman-Monteith method (Fig. 3b).

Consequently, an attempt was made for crop coefficient calculation (Eq. 33) proper for determination of potential evapotranspiration with the Penman-Monteith method. The following croplands were taken under consideration: pasture located in Warmia Region and intensive meadow, extensive meadow and natural wetland plant communities characteristic of Middle Biebrza River Basin. The calculation was conducted for vegetation period decade values of Modified Penman and Penman-Monteith reference evapotranspiration and crop coefficient for the Modified Penman method elaborated by Roguski et al. (1988), Brandyk et al. (1996) and Szuniewicz & Chrzanowski (1996). Considered values of crop coefficient both for Modified Penman ($k_{c\text{ MP}}$) and Penman-Monteith ($k_{c\text{ P-M}}$) for pasture was presented on Table 1. It can be maintain that $k_{c\text{ P-M}}$ values for April are about 0.05 lower than $k_{c\text{ MP}}$ values. The values for May, June and July are the same or almost the same – the difference does not exceed 0.02. The most significant differences are present in September, where $k_{c\text{ P-M}}$ is lower than $k_{c\text{ MP}}$ from 0.09 to 0.21.

Month	Decade	Crop coefficient	
		$k_{c\text{ MP}}$	$k_{c\text{ P-M}}$
April	1	0.75	0.70
	2	0.80	0.76
	3	0.80	0.76
May	1	0.85	0.84
	2	0.80	0.81
	3	0.95	0.95
June	1	0.70	0.71
	2	0.70	0.71
	3	0.95	0.97
July	1	0.80	0.81
	2	0.85	0.85
	3	0.90	0.89
August	1	0.80	0.79
	2	0.95	0.93
	3	1.05	1.00
September	1	0.95	0.86
	2	1.00	0.87
	3	1.10	0.89

Table 1. Crop coefficient of pasture for Modified Penman and Penman-Monteith methods

Modified Penman crop coefficient for extensive meadows (EM) and natural wetlands plant communities (NWPC) was published by Brandyk et al. (1996) as cited in: Roguski (1985) and Łabędzki & Kasperska (1994). Values of these crop coefficients as well as values of calculated Penman-Monteith crop coefficients was presented on Table 2. It can be maintain that $k_{c\text{ P-M}}$ values are higher than $k_{c\text{ MP}}$ values from 0.01 to 0.12 for extensive meadow in

general. An exception to this rule is the last five decades, when $k_{c\text{ P-M}}$ values are lower then $k_{c\text{ MP}}$ values from 0.01 to 0.23. A similar tendency can be observed for natural wetland plant communities. But wider differences occur between $k_{c\text{ P-M}}$ and $k_{c\text{ MP}}$. A value of $k_{c\text{ P-M}}$ is higher up to 0.08 than $k_{c\text{ MP}}$ value for a few decades and lower until 0.31 for the last decade of September.

Month	Decade	Crop coefficient			
		EM		NWPC	
		$k_{c\text{ MP}}$	$k_{c\text{ P-M}}$	$k_{c\text{ MP}}$	$k_{c\text{ P-M}}$
April	1	0.93	1.05	0.62	0.70
	2	0.93	0.97	0.79	0.83
	3	0.85	0.84	0.75	0.74
May	1	0.88	0.90	0.77	0.79
	2	1.04	1.09	1.06	1.10
	3	1.03	1.08	1.21	1.27
June	1	0.76	0.79	1.24	1.30
	2	0.91	0.96	1.28	1.36
	3	0.98	1.04	1.40	1.48
July	1	0.99	1.03	1.32	1.37
	2	1.01	1.06	1.18	1.23
	3	0.98	1.04	1.40	1.48
August	1	0.97	0.98	1.30	1.31
	2	1.07	1.07	1.40	1.39
	3	1.18	1.15	1.40	1.36
September	1	1.34	1.27	1.63	1.55
	2	1.41	1.27	1.85	1.66
	3	1.41	1.18		1.60

Table 2. Crop coefficient of extensive meadow and natural wetland plant communities for Modified Penman and Penman-Monteith methods

The Modified Penman crop coefficient for intensive meadow located in Middle Biebrza River Basin was elaborated by Szuniewicz & Chrzanowski (1996). They based the research on lysimeter experiments conducted on peat -moorsh soil with a ground water level of 35 – 90 cm (optimum soil moisture) during the 1982-1991 period. Researchers had established conditions for 3-cut meadows with different hay yields: 0.10, 0.20, 0.30, 0.40 and 0.50 Mg ha⁻¹. The climate of the considered region is more severe compared to other plain regions in Poland, thus the vegetation period starts about two weeks later. Elaborated by Szuniewicz & Chrzanowski crop coefficients for the Modified Penman method as well as calculated crop coefficients for Penman-Monteith was presented on Table 2. There are not significant differences between $k_{c\text{ P-M}}$ and $k_{c\text{ MP}}$ values for the first two decades of the vegetation period.

The differences increase during successive decades of May and June from 0.02 up to 0.07. Next, they decrease from 0.04 to 0.02 in July. There are not significant differences again for first and second decades of July. The difference begins it's increase from the third decade of July up to the second decade of September. The values of $k_{c\ P-M}$ are even 0.12 – 0.18 lower than $k_{c\ MP}$ for the second decade of September. There is also a clear tendency towards an increase of differences between crop coefficients $k_{c\ P-M}$ and $k_{c\ MP}$ values due to an increase of potential hay yield. The $k_{c\ P-M}$ values get higher from 0.02 to 0.07 in May and June. However, the opposite tendency can be observed in September, when $k_{c\ P-M}$ get lower from 0.06 to even 0.18.

Month	Decade	Cut	Crop coefficient at hay yields Mg ha ⁻¹									
			0.10		0.20		0.30		0.40		0.50	
			$k_{c\ MP}$	$k_{c\ P-M}$	$k_{c\ MP}$	$k_{c\ P-M}$	$k_{c\ MP}$	$k_{c\ P-M}$	$k_{c\ MP}$	$k_{c\ P-M}$	$k_{c\ MP}$	$k_{c\ P-M}$
April	2	I	0.93	0.96	0.93	0.96	0.93	0.96	0.93	0.96	0.93	0.96
	3		0.78	0.77	0.85	0.84	0.9	0.89	0.95	0.94	0.99	0.98
May	1		0.77	0.79	0.88	0.90	0.97	0.99	1.06	1.08	1.13	1.15
	2		0.89	0.93	1.04	1.09	1.17	1.22	1.28	1.34	1.39	1.45
	3		0.86	0.90	1.03	1.08	1.18	1.24	1.31	1.38	1.43	1.50
June	1	II	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80
	2		0.86	0.91	0.91	0.96	0.95	1.01	0.99	1.05	1.02	1.08
	3		0.87	0.92	0.98	1.04	1.08	1.14	1.17	1.24	1.25	1.32
July	1		0.85	0.89	0.99	1.03	1.11	1.16	1.21	1.26	1.30	1.36
	2		0.86	0.90	1.01	1.06	1.15	1.20	1.27	1.33	1.38	1.44
	3		0.78	0.80	0.78	0.80	0.78	0.80	0.78	0.80		
August	1	III	0.89	0.90	0.97	0.98	1.04	1.05	1.09	1.10		
	2		0.95	0.94	1.07	1.06	1.17	1.16	1.26	1.25		
	3		0.96	0.94	1.18	1.15	1.36	1.33	1.52	1.48		
September	1		1.12	1.06	1.34	1.27	1.52	1.44	1.68	1.59		
	2		1.16	1.04	1.41	1.27	1.63	1.47	1.82	1.64		

Table 3. Crop coefficient of 3-cut meadow for Modified Penman and Penman-Monteith methods

The next step of this work use to be an comparison potential evapotranspiration calculated as a product of Penman-Monteith reference evapotranspiration and determined crop coefficient ($k_{c\ P-M}$) with alternative potential evapotranspiration by Thornthwaite. In order to solve the problem, decade values of Thornthwaite potential evapotranspiration was calculated (Eq. 34-37) and Penman-Monteith potential evapotranpiration applying crop coefficient for proper land use. The relationship between Thornthwaite potential

evapotranspiration and Penman-Monteith potential evapotranspiration was presented on Fig. 4. The relationship was fitted by linear regression through origin. Analyzing obtained results, it can be maintain that Penman-Monteith evapotranspiration values are lower by about 25% for pasture (Fig. 4a) and 8% for extensive meadow than the Thornthwaite method

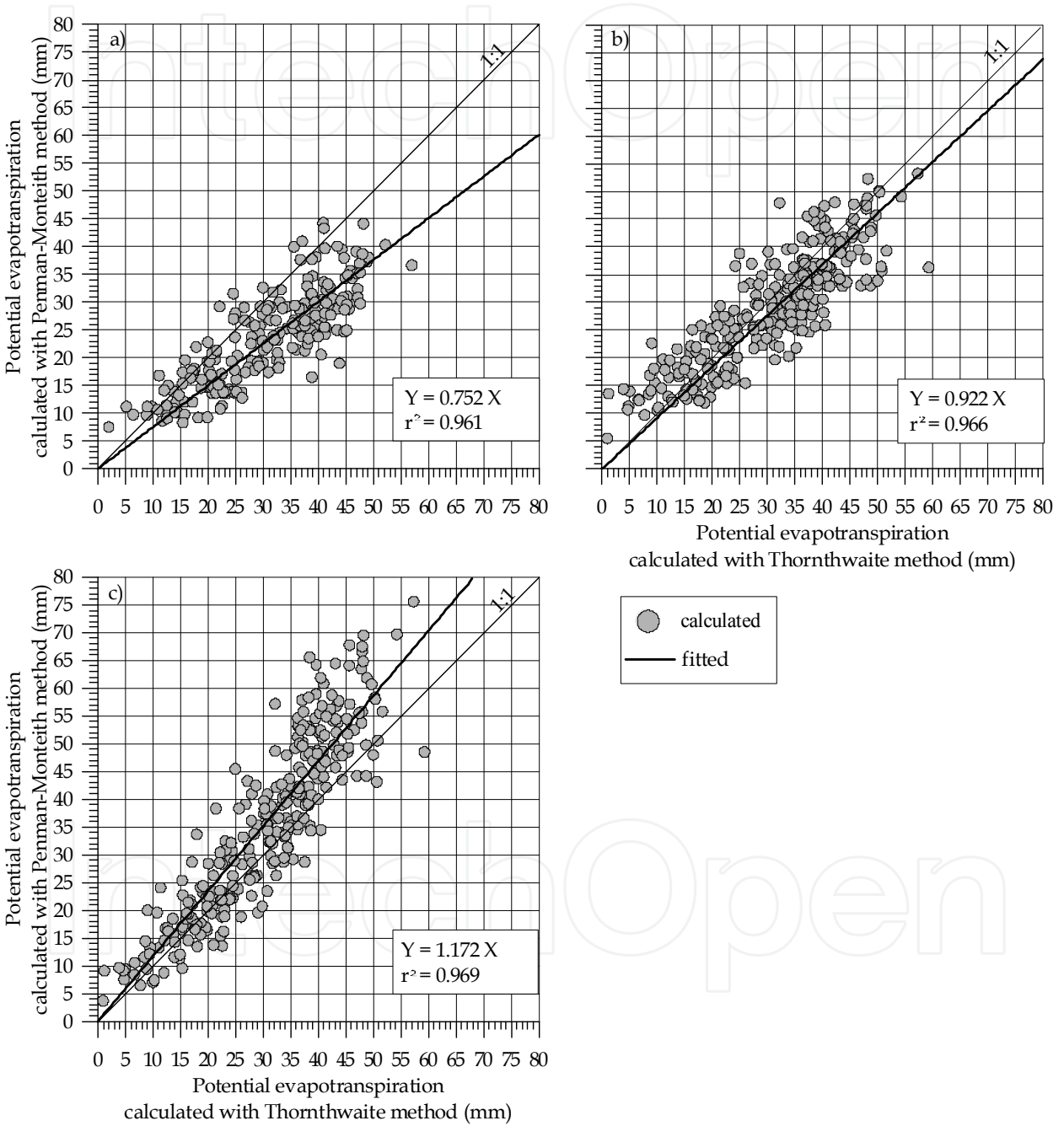


Fig. 4. The relationship between Thornthwaite potential evapotranspiration and Penman potential evapotranspiration for: pasture (a), extensive meadow (b) and natural wetland plant communities (c)

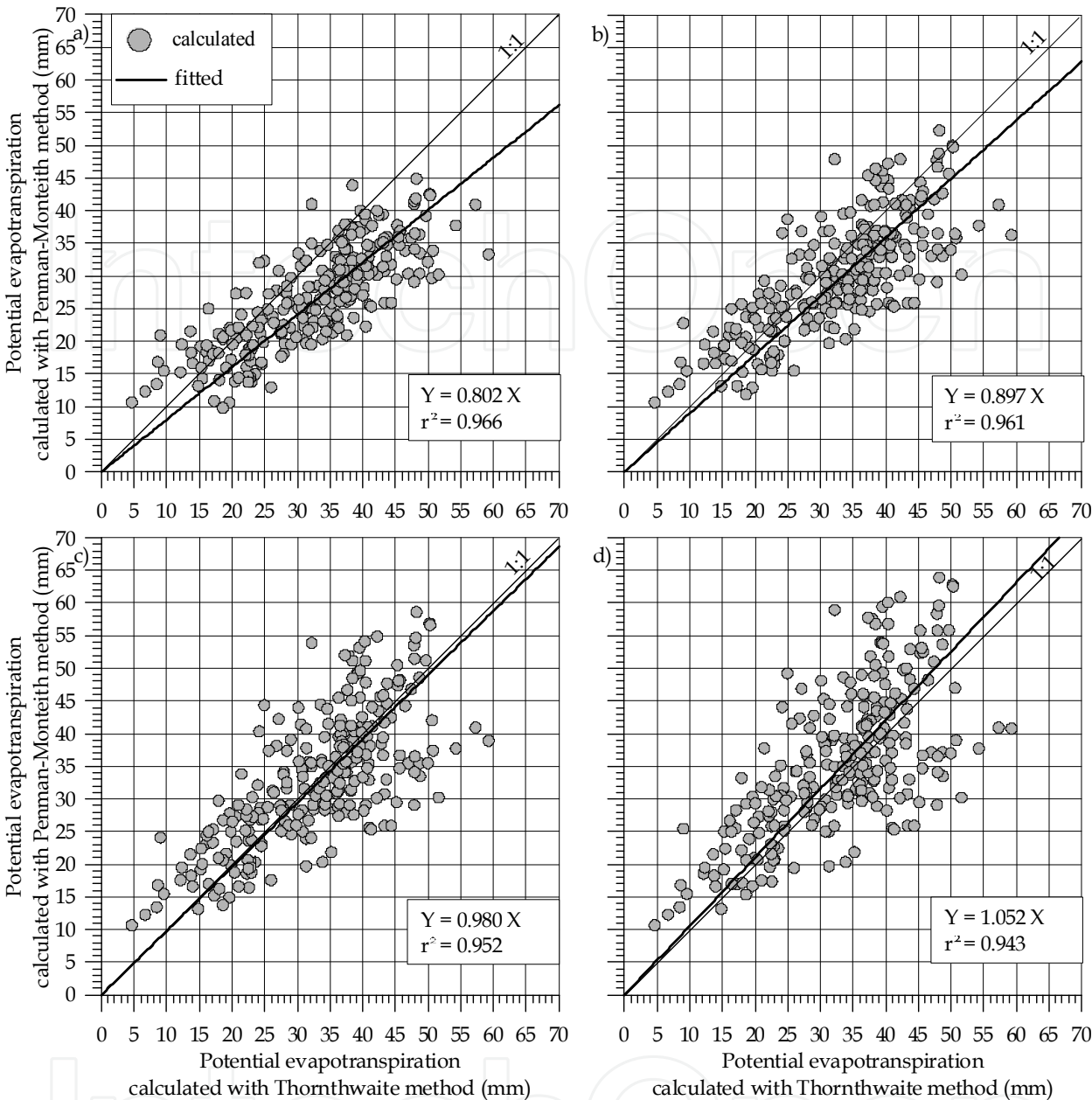


Fig. 5. The relationship between Thornthwaite potential evapotranspiration and Penman potential evapotranspiration of 3-cut meadow for hay yield Mg ha^{-1} : 0.10 (a), 0.20 (b), 0.30 (c) and 0.40 (d)

(Fig. 4b). Whereas in case of natural wetland plan community evapotranspiration, values calculated with Penman-Monteith method are of about 17% higher then values calculated with Thornthwaite method. It must to be noted, that coefficient of determination is almost equal ($r^2 \approx 97\%$) for all three cases. The relationship between Thornthwaite potential evapotranspiration and Penman-Monteith potential evapotranspiration for 3-cut meadow was presented on Fig. 5. Analyzing obtained results, it can be maintained that Penman-Monteith evapotranspiration values are very close to Thornthwaite evapotranspiration values for 0.30 Mg ha^{-1} hay yield. An evapotranspiration calculated with the Thornthwaite method is just about 2% higher than Penman-Monteith evapotranspiration. The highest overestimation (20%) of the Thornthwaite method is observed for the lowest hay yield

(0.10 Mg ha⁻¹). The case of 0.20 Mg ha⁻¹ hay yield characterizes about a 10% overestimation of the Thornthwaite method. An opposite case is the case of 0.40 Mg ha⁻¹ hay yield, where the Thornthwaite method underestimates evapotranspiration by about 5%. Coefficients of determination vary between 94.3% (0.40 Mg ha⁻¹ hay yield) and 96.6% (0.10 Mg ha⁻¹ hay yield).

5. Conclusion

Based on the performed research the following conclusions can be formulated:

There are not significant differences between reference evapotranspiration calculated with the Modified Penman and Penman-Monteith methods of the Warmia Region as well as Middle Biebrza River Basin for entire vegetation period (April – September). Due to linear equation, Penman-Monteith reference evapotranspiration values are about 1.6 % higher than values calculated by the Modified Penman method for the Warmia Region case. Whereas, values of Modified Penman reference evapotranspiration are about 2.0% lower than values obtained with the Penman-Monteith method. From a practical point of view, the difference of total vegetation period reference evapotranspiration equals about 8 mm for the Warmia Region and 10 mm for Middle Biebrza River Basin due to 513 mm (Warmia Region) and 486 mm (Middle Biebrza River Basin) of average vegetation period reference evapotranspiration assumption.

Crop coefficients calculated for the Penman-Monteith evapotranspiration method are comparable or lower than crop coefficients for the Modified Penman method in case of pasture. Taking under consideration crop coefficient differences for extensive meadow and natural wetland plant communities it can be found that $k_{c\ P-M}$ values are higher than $k_{c\ MP}$ values from 0.01 to 0.12 for most of the vegetation period in general. An exception to this rule is the last five decades, when $k_{c\ P-M}$ values were lower than $k_{c\ MP}$ values from 0.01 even to 0.31. There are not significant differences between $k_{c\ P-M}$ and $k_{c\ MP}$ values for the first and second decades of vegetation period as well as for the first and second decades of July in the case of 3-cut meadow. The difference begins to from the third decade of July up to the second decade of September. The values of $k_{c\ P-M}$ are even 0.12 – 0.18 lower than $k_{c\ MP}$ for the second decade of September. Summarizing, crop coefficients calculated for Penman-Monteith method are almost equal or slightly higher compare to Modified Penman crop coefficients for most of a vegetation period in all considered land use. An exception are last three to four decades of vegetation period when values of $k_{c\ P-M}$ are clearly lower compared to $k_{c\ MP}$ values. These differences are equal during the entire vegetation period. But they can have essential meaning in certain parts (decades) of vegetation period when a crop water requirement is determined.

Potential evapotranspiration values calculated with the Thornthwaite method are overestimated in ratio to values calculated with the Penman-Monteith method in the following cases by about: 25% for pasture, 20% for 3-cut meadow (0.10 Mg ha⁻¹ hay yield), 10% for 3-cut meadow (0.20 Mg ha⁻¹ hay yield) and 8% for extensive meadow. Whereas, one time Thornthwaite potential evapotranspiration values were lower by about 5% for 3-cut meadow (0.40 Mg ha⁻¹ hay yield). The best convergence of the considered methods is observed for 3-cut meadow in case of 0.30 Mg ha⁻¹. It has to be said, that coefficient of determination r^2 exceeds 94% of the value for all cases. Summarized, the Thornthwaite potential evapotranspiration method is comparable with the Penman-Monteith method for 3-cut meadow with a high value of hay yield and extensive meadow.

Future research should be focused on trials to find correlations between Thornthwaite and Penman-Monteith potential evapotranspiration for individual months of vegetation period. Another aim could be crop coefficient calculation for the Penman-Monteith method for field crops like grains, potatoes or sugar beets.

6. Acknowledgment

A part of this work considered to evapotranspiration calculation of Warmia Region was supported by the grant of Polish Ministry of Science and Higher Education No N N305 039234.

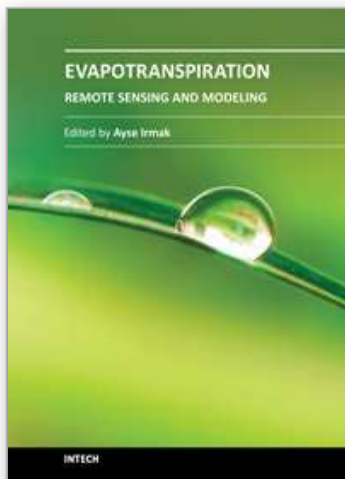
Special thanks to friend of mine Dr Jan Szatyłowicz for help with Penman's methods evapotranspiration calculation for Middle Biebrza River Basin.

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Evapotranspiration - Remote Sensing and Modeling

Edited by Dr. Ayse Irmak

ISBN 978-953-307-808-3

Hard cover, 514 pages

Publisher InTech

Published online 18, January, 2012

Published in print edition January, 2012

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Daniel Szejba (2012). Evapotranspiration of Grasslands and Pastures in North-Eastern Part of Poland, Evapotranspiration - Remote Sensing and Modeling, Dr. Ayse Irmak (Ed.), ISBN: 978-953-307-808-3, InTech, Available from: <http://www.intechopen.com/books/evapotranspiration-remote-sensing-and-modeling/evapotranspiration-of-grasslands-and-pastures-in-north-eastern-part-of-poland>

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