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Estimation of Reference Evapotranspiration using the FAO Penman-Monteith Method for Climatic Conditions of Poland

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1. Introduction

Evapotranspiration is the combination of soil evaporation and crop transpiration. Weather parameters, crop characteristics, management and environmental factors affect evapotranspiration. Reference, potential and actual evapotranspiration are distinguished. These terms are commonly used, although some differences of their definitions can be found among researches.

The potential evapotranspiration of a given crop is defined as soil evaporation and plant transpiration under unlimited soil water supply and actual meteorological conditions. According to Brutseart (1982) the potential evapotranspiration is a maximum intensity of evapotranspiration from a large surface covered completely and homogeneously with actively growing plants under conditions of unlimited availability of soil water. Allen et al. (1998) call it the crop evapotranspiration under standard conditions and define as the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions and achieving full production under the given climatic conditions.

The actual evapotranspiration is the amount of water transpired from plants and evaporated from soil surface under actual meteorological conditions and under non-optimal soil, biological, management and environmental conditions. It differs from the potential evapotranspiration due to soil water shortage or waterlogging, diseases, soil salinity, low soil fertility. According to Allen et al. (1998) the evapotranspiration from crops grown under management and environmental conditions that differ from the standard conditions defined for the potential evapotranspiration can be called the crop evapotranspiration under non-standard conditions.

The evapotranspiration from a reference surface is called the reference evapotranspiration and is denoted as ET_o. A large uniform grass (or alfalfa) field is considered worldwide as the reference surface. The reference grass crop completely covers the soil, is kept short, well watered and is actively growing under optimal agronomic conditions.

Reference evapotranspiration (ET_o) is an important agrometeorological parameter for climatological and hydrological studies, as well as for irrigation planning and management. There are several methods to estimate ET_o. The FAO Penman-Monteith (FAO PM) method has been considered as a universal standard to estimate ET_o (Allen et al., 1989, 1994, 1998;

Feddes & Lenselink, 1994; Smith, 1992). The method is recommended to use as the international standard for definition and estimation of reference crop evapotranspiration.

The reference evapotranspiration describes the evaporative demand of the atmosphere independently of crop type, crop development and management practices. As water is available sufficiently, soil factors do not affect ET_o. Relating evapotranspiration to a specific surface provides a reference to which evapotranspiration from other surfaces can be related. The evapotranspiration from cropped surfaces other than the reference surface can be calculated with the crop factor method using the crop coefficient (under standard conditions) and water stress coefficient (under soil water stress conditions). To estimate crop water requirements, one can relate potential evapotranspiration from the cropped soil with an optimum water supply to an estimated reference evapotranspiration by means of a crop coefficient.

ET_o values measured or calculated at different locations or in different seasons are comparable as they refer to the evapotranspiration from the same reference surface. The only factors affecting ET_o are climatic parameters. ET_o is an agro-climatic parameter and can be computed from weather data. ET_o expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors (Allen et al., 1998).

The FAO PM method considers many meteorological parameters related to the evapotranspiration process (net radiation, air temperature, vapor pressure deficit, wind speed) and has presented very good results when compared to data from lysimeters populated with short grass (Allen et al., 2006). Labedzki (1999) found a good agreement between the calculated FAO PM reference evapotranspiration and measured evapotranspiration in lysimeters covered with grass with standardized parameters under climatic conditions of central Poland. The linear correlation coefficient was r=0.997 and the standard error of estimation SEE=0.45 mm day^{-1}. Allen et al. (1989, 1994) obtained similar values (r=0.82-0.99 and SEE=0.09-0.77 mm day^{-1}) for lysimeter measurements carried out in different locations in USA.

There are many researches who carried out the analysis of the FAO PM method and the reference evapotranspiration calculated with this method from the point of view of its spatial distribution (e.g. Buttafuoco et al., 2010; McVicar et al., 2007; Song et al., 2010), its accuracy and sensivity (e.g. Allen et al., 2005; Buttafuoco et al., 2010; Fitzmaurice & Beswick, 2005), in relation to other methods of calculating reference evapotranspiration (e.g. Maulé et al., 2006; Paltineanu et al., 1999; Sumner &. Jacobs, 2005).

The objective of this study was to evaluate the performance of the FAO PM method to estimate ET_o under climatic conditions of Poland. The analysis of temporal and spatial variability of the PM reference evapotranspiration is contained as well as the application of the reference evapotranspiration to the determination of agro-climatic regions and climatic water balance in Poland.

2. Climate of Poland

Poland is situated in the Great European Plain between the Baltic Sea and the Carpathian mountains. It is located in a transitory temperate climate zone, influenced by a mild oceanic climate from the west and a dry continental climate from the east. The geographical location of Poland facilitates the occurrence of a great diversity of weather and climatic conditions. The major atmospheric systems shaping the weather conditions in Poland are the yearlong

Icelandic Low and Azorian High in the west and, to a lesser extent, the seasonal Asian High (Wos, 1999). Climatic conditions in Poland are characterized by a considerable variability in weather during long periods of time (years) as well as short periods (days, weeks, months). The annual precipitation amounts to 600 mm. It reaches 350 mm on the average during the vegetation period (April - September). In this period precipitation ranges from 300 mm in the central part to 400 mm in the northern Poland and to 600 mm in the southern Poland (Fig. 1). Taking into account precipitation tendencies in the period 1891-2000, it can be distinguished, in general, three main regions: northern – with an increasing precipitation tendency, central – with a decreasing precipitation tendency and the southern one – without any significant tendency. The clearest tendencies are visible between individual stations. The statistically lowest difference of 55 mm should be accepted as the value characteristic for the total area of Poland (Zawora & Ziernicka, 2003).

Due to the shortage of precipitation and the increase trend of temperature, drought frequency has increased, particularly during the last decade. The dry regions of Poland are almost the entire central region, as well as north-western and mid-eastern parts. These are the regions most threatened by droughts with the annual rainfall amount often less than 300 mm. The most frequent and most severe droughts occur in this area, which sometimes experiences extremely long periods without rain. It is commonly assumed that droughts appear in Poland once every 4-5 years (Labedzki, 2007). Drought usually begins in western Poland, moves through the central part and eventually reaches eastern side. Droughts have become a severe problem in Polish agriculture. They are the main reason for decline in crop yields.
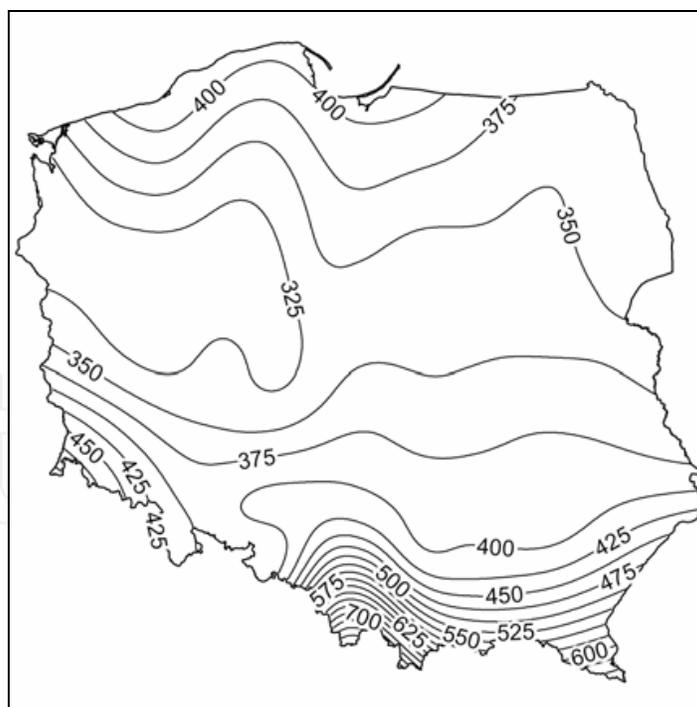

Fig. 1. Precipitation [mm] in the growing season (Apr-Sep), the mean values in 1970-2004

The annual mean temperature is +7.5°C. Averages of temperature in Poland in the 20th century varied from 6°C to over 9°C, with tendency for 7-year periodicity and revealed an increasing trend, which means the warming up reaching 0.9°C per 100 years (Kozuchowski & Zmudzka, 2003). The mean temperature amounts from -2.5°C in January to 18°C in July.

The maximum temperature often rises to above 30°C in summer. According to Kejna et al. (2009) the distribution of Tmin is meridional, with high values in the west and on the Baltic coast (4–5°C), and lowest in the east (2.5°C). In the period 1951–2005 a statistically significant increase of Tmin occurred in north-west Poland, reaching 0.2–0.3°C per 10 years. The highest mean Tmax are in the west of Poland (up to 12°C) and they decrease eastwards and on the coast (10.5°C). In most of the country they increase (up to 0.26°C/10 years), though the changes in south-east Poland are not significant. The number of days with Tmin<0°C varied from less than 100 days on the Baltic coast to over 140 days in the east of Poland. Their frequency drops almost throughout the country, and by as much as 4.3 days per 10 years in the north. The frequency of days with Tmin<-10°C in Poland oscillated between 10 on the coast to 40 in the east, showing a significant growth only in the south (by 2–3 days/10 years). Days with Tmin<-20°C are sporadic (1–8) and their frequency grows in south-east Poland (by 1.2 days/10 years). Days with Tmin<-30°C are very rare (less than 1). Hot days (Tmax>25°C) occur from 15–20 times a year on the coast and 25 in the south to over 30 times in the centre of the Poland. Throughout country the number of hot days increases by up to 4.6 days/10 years. Similarly, the number of very hot days (Tmax>30°C) has increased to 1.4 days in the Pomeranian Lake District (north-western Poland). Their frequency ranges from 2 to 6 days per year. Extremely hot days (Tmax>35°C) are very sporadic in Poland (less than 1 day per year) and their frequency has also slightly increased.

3. Calculation of reference evapotranspiration ET_o

3.1 Method

The general form Penman-Monteith equation (Allen et al., 1998) is:

$$\lambda \, ET = \frac{\Delta \, (R_n - G) + \rho c_p \, (e_s - e_a)/r_a}{\Delta + \gamma \, (1 + r_c/r_a)} \tag{1}$$

where ET is evapotranspiration, R_n is the net radiation, G is the soil heat flux, $(e_s - e_a)$ is the vapour pressure deficit of the air, γ is the psychrometric constant, Δ is the slope of the vapour pressure curve, λ is the latent heat of vaporization, c_p is the specific heat of moist air at constant pressure, ρ is the air density, r_a is the aerodynamic resistance to turbulent heat and vapor transfer, r_c is the surface resistance.

This equation can be applied to different vegetation and soil moisture conditions. By defining the reference crop as a actively growing and well watered green grass surface with a height of 0.12 m having a surface resistance of 70 s·m^{-1} and an albedo of 0.23, the FAO Penman-Monteith method to estimate ET_o can be derived as (Allen et al., 1998):

$$ET_o = \frac{0.408 \, \Delta(R_n - G) + 900 \, \gamma u_2(e_s - e_a)/(T + 273)}{\Delta + \gamma \, (1 + 0.34 \, u_2)} \tag{2}$$

where:

ET_o - reference evapotranspiration [mm day^{-1}],

R_n - net radiation [MJ m^{-2} day^{-1}],

G - soil heat flux density [MJ m^{-2} day^{-1}],

T - mean daily air temperature at 2 m height [°C],

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u_2 - wind speed at 2 m height [m s^{-1}],

e_s - saturation vapour pressure [kPa],

e_a - actual vapour pressure [kPa],

e_s-e_a - saturation vapour pressure deficit [kPa],

Δ - slope of the vapour pressure curve [kPa °C^{-1}],

γ - psychrometric constant [kPa °C^{-1}].

The time step with which ET_o is calculated depends on the purpose of the calculation, the required accuracy and the time step of the meteorological data available. Several data in Equation (2) are not measured directly and they should be computed. The method of computation of such data also depends on the meteorological data available.

For the purpose of this study ET_o was calculated with the ten-day time step. Allen et al. (1998) write that, notwithstanding the non-linearity in the Penman-Monteith equation and some weather parameter methods, mean ten-day weather data can be used to compute the mean ten-day values for the reference evapotranspiration. The value of the reference evapotranspiration calculated with mean ten-day weather data is similar to the average of the daily ET_o values calculated with daily average weather data.

Using Equation (2) the mean ten-day values of ET_o are calculated in the growing period (April – September) of 1970-2004 for the mean ten-day values of R_n, T, u_2, e_s and e_a. Then the ten-day sums of ET_o are calculated by multiplying the mean ten-day values by 10 or 11. The monthly and the whole period sums are computed as the sums of the ten-day sums.

The net radiation R_n is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net longwave radiation (R_{nl}):

$$R_n = R_{ns} – R_{nl} \tag{3}$$

The net shortwave radiation R_{ns} resulting from the balance between incoming and reflected solar radiation is calculated as:

$$R_{ns} = (1 - a) \, R_s \tag{4}$$

where:

R_{ns} - net solar shortwave radiation [MJ m^{-2} day^{-1}],

a - albedo = 0.23 for the hypothetical grass reference crop [dimensionless],

R_s - incoming solar radiation [MJ m^{-2} day^{-1}].

Because the solar radiation R_s was not measured, it was calculated with the Angstrom formula which relates solar radiation to extraterrestrial radiation and relative sunshine duration, in the form with the constants according to Allen et al. (1998):

$$R_s = (0.25 + 0.50 \, S/S_o) \, R_a \tag{5}$$

where:

S - actual duration of sunshine [hour],

S_o - maximum possible duration of sunshine or daylight hours [hour],

R_a - extraterrestrial radiation [MJ m^{-2} day^{-1}].

The extraterrestrial radiation R_a and the maximum possible daylight hours S_o for a specific day of the month and a given latitude are taken from Sun Tables (1974).

The outgoing net longwave radiation R_{nl} is calculated from the equation (Allen et al., 1998):

$$R_{nl} = \sigma T^4 (0.34 – 0.14\sqrt{e_a})(1.35 \, R_s/R_{so} – 0.35) \tag{6}$$

where:

R_{nl} - net longwave radiation [MJ m^{-2} day^{-1}],

σ - Stefan-Boltzmann constant [4.903 10^{-9} MJ K^{-4} m^{-2} day^{-1}],

T – mean ten-day temperature [K],

R_{so} – clear-sky radiation [MJ m^{-2} day^{-1}], calculated as:

$$R_{so} = 0.75\ R_a \tag{7}$$

Saturation vapour pressure e_s was calculated from the relationship:

$$e_s = 0.611 \exp[17.27T/(T+237.3)] \tag{8}$$

where:

e_s - saturation vapour pressure [kPa],

T - mean ten-day air temperature [^{o}C].

Actual vapour pressure e_a was calculated as:

$$e_a = e_s\ RH/100 \tag{9}$$

where:

e_a - actual vapour pressure [kPa],

RH - mean ten-day relative humidity [%].

The slope of the relationship between saturation vapour pressure and temperature is given by:

$$\Delta = 4098\ e_s\ /(T + 237.3)^2 \tag{10}$$

where:

Δ - slope of the vapour pressure curve [kPa °C^{-1}],

T – mean ten-day temperature air temperature [°C].

Because soil heat flux G is small compared to R_n, when the surface is fully covered by vegetation and the calculation time step is ten days, the estimation of G can be ignored and assumed to be zero in Equation (2). Allen et al. (1998) state that the soil heat flux beneath the grass reference surface is relatively small for that time period.

The sums of reference evapotranspiration ET_o in each month and in the whole growing period from April to September in the years 1970-2004 were established at 40 meteorological stations located in different regions of Poland. The statistical analysis was performed to get the values of mean, minimum, maximum, standard deviation, variability coefficient and median.

Statistical parameters characterizing the temporal variability of ET_o are determined using ET_o averaged over 40 stations in each year.

Statistical parameters characterizing the spatial variability of ET_o are determined using ET_o averaged over 35 years at each station. The gamma probability distributions were fitted to the multi-year series of the sums of ET_o in the growing season at each station, checking goodness-of-fit by using the χ^2-Pearson test. On that basis the sums of ET_o at the probability of exceeding of 0.2, 0.5 and 0.8 were estimated.

The sums of reference evapotranspiration in the growing season were used to distinguish the agro-climatic regions of Poland with the *k*-means clustering algorithm.

The same sums of ET_o were used to calculate the climatic water balance in the growing period. Climatic water balance is the difference between precipitation sum P and reference evapotranspiration ET_o calculated according to the Penman-Monteith formula:

$$CWB = P - ET_o \tag{11}$$

where:

CWB – climatic water balance [mm],

P – precipitation [mm],

ET_o - reference evapotranspiration according to the Penman-Monteith method [mm].

The maps of the spatial distributions of ET_o (the sums in the growing season at the probability of 0.2, 0.5 and 0.8, the mean monthly sums) and of CWB (the sums in the growing season) were created using the Regularized Spline Radial Basic Function method with the Spatial Analyst Module of ArcView GIS 9.1.

3.2 Data

The ten-day records of meteorological parameters (air temperature, air humidity, sunshine hours, wind velocity and precipitation) came from 40 meteorological stations of the Institute of Meteorology and Water Resources and of the Institute of Technology and Life Sciences (Tab. 1, Fig. 2).
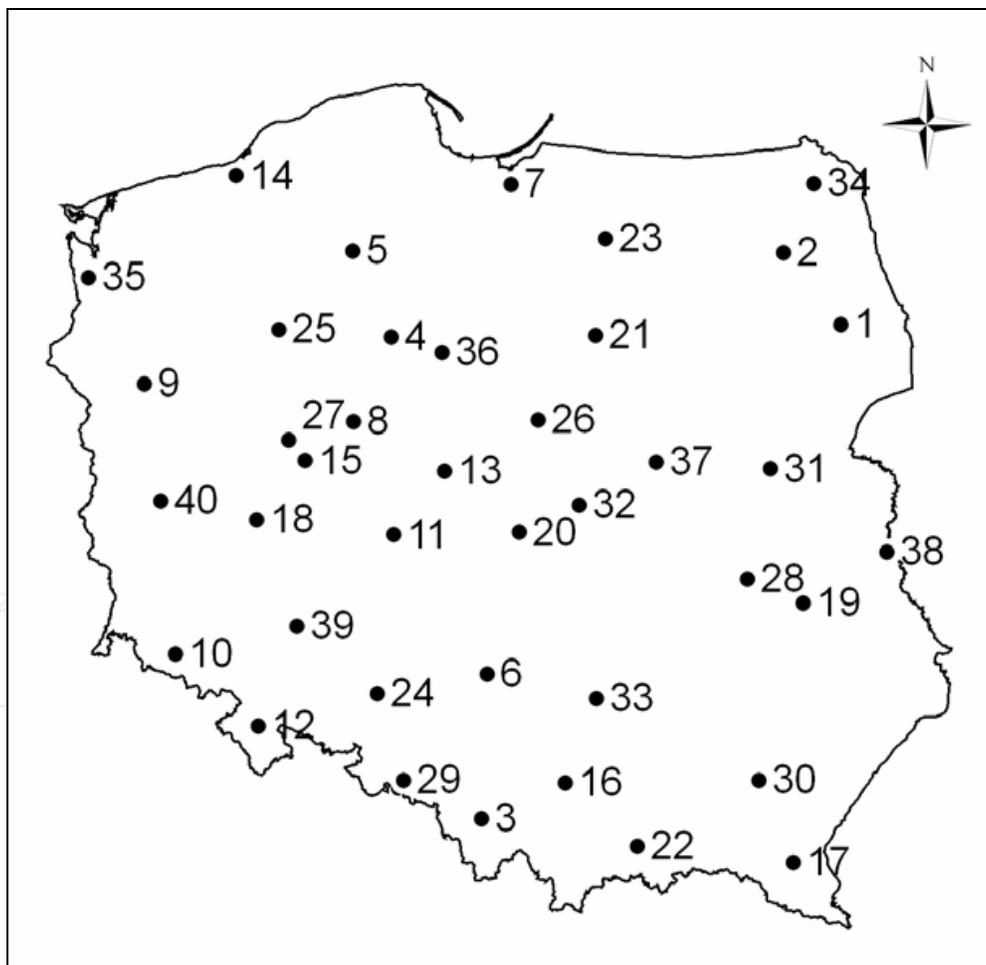

Fig. 2. Geographical location of the studied meteorological stations in Poland (1 – the number of the station from Tab. 1)

No	Station	Altitude (m a.s.l.) *	Latitude	Longitude
1	Białystok	139	53o13'	23o10'
2	Biebrza	117	53o39'	22o36'
3	Bielsko-Biała	398	49o48'	19o00'
4	Bydgoszcz	46	53o08'	18o01'
5	Chojnice	173	53o42'	17o33'
6	Częstochowa	261	50o49'	19o06'
7	Elbląg	38	54o10'	19o26'
8	Gniezno	110	52o33'	17o34'
9	Gorzów	65	52o44'	15o15'
10	Jelenia Góra	342	50o54'	15o48'
11	Kalisz	140	51o44'	18o05'
12	Kłodzko	316	50o26'	16o39'
13	Koło	95	52o12'	18o40'
14	Koszalin	33	54o12'	16o09'
15	Kórnik	77	52o15'	17o06'
16	Kraków	209	50o04'	19o57'
17	Lesko	386	49o28'	22o20'
18	Leszno	93	51o51'	16o35'
19	Lublin	171	51o14'	22o34'
20	Łódź	184	51o44'	19o24'
21	Mława	141	53o06'	20o21'
22	Nowy Sącz	292	49o37'	20o41'
23	Olsztyn	133	53o46'	20o25'
24	Opole	176	50o40'	17o58'
25	Piła	72	53o08'	16o45'
26	Płock	62	52o33'	19o40'
27	Poznań	86	52o25'	16o50'
28	Puławy	142	51o25'	21o58'
29	Racibórz	190	50o05'	18o13'
30	Rzeszów	200	50o06'	22o03'
31	Siedlce	146	52o11'	22o16'
32	Skierniewice	129	51o57'	20o09'
33	Skroniów	256	50o38'	20o16'
34	Suwałki	165	54o08'	22o57'
35	Szczecin	1	53o24'	14o37'
36	Toruń	69	53o03'	18o35'
37	Warszawa	106	52o09'	20o59'
38	Włodawa	175	51o38'	23o33'
39	Wrocław	116	51o06'	17o05'
40	Zielona Góra	182	51o56'	15o30'

* m a.s.l. metres above mean sea level

Table 1. Geographical location of the studied meteorological stations

4. Reference evapotranspiration ET_o

4.1 Temporal variability of ET_o

The monthly and the growing season sums of ET_o, averaged over 40 stations, characterise the multi-year mean reference evapotranspiration in Poland. In particular months it ranges from 54 mm in September to 110 mm in July (Tab. 2). It means the mean daily reference evapotranspiration from almost of 2 mm day^{-1} to 4 mm day^{-1}, respectively. The highest monthly sum (157 mm) occured in July 1994 and the lowest (42 mm) in September 2001.

In the whole vegetation period, from April to September, ET_o amounts to 520 mm. Taking into account the average precipitation in this period equal to 350 mm, water deficit can be expected in Poland, on average. During 1970-2004, the lowest whole-country mean ET_o (422 mm) occured in 1980 and the highest ET_o (615 mm) in 1992 (Tab. 2, Fig. 3). The 1980 was a very wet year with the highest precipitation in most regions of Poland, whereas in 1992 the extreme drought occured all other the country, caused by very low precipitation, high air temperature and high insolation. The close relationship between reference evapotranspiration and precipitation is a characteristic feature of a transitory temperate climate. Reference evapotranspiration had rather high temporal variability in the multi-year period, with the variability coefficient of 12-15% for the monthly sums and 9% for the sums in the growing season. It is the other special feature of climate in Poland.

Parameter	Period						
	Apr	May	June	July	Aug	Sep	Apr-Sep
Mean [mm]	61	97	104	110	96	54	520
Minimum [mm]	50	78	80	77	75	42	422
Maximum [mm]	83	116	134	157	123	71	615
Median [mm]	59	96	102	107	96	52	516
Standard deviation [mm]	8	11	13	17	12	8	46
Variability coefficient [%]	13	12	13	15	13	14	9

Table 2. Statistics of temporal variability of ET_o averaged over 40 stations

ET_o changed in a wide range in 1970-2004. The amplitude (maximum-minimum) of the ET_o sums in the growing season was the lowest in southern Poland (135 mm) and the highest in central Poland (316 mm). It shows that meteorological conditions were more stable in southern Poland than in central.

The statistically significant linear increasing trend of the growing season spatially averaged reference evapotranspiration was determined in the analyzed period 1970-2004 (Fig. 3). The trend shows the increase of 27 mm per 10 years and is an effect of the increasing trends of temperature, sunshine hours and solar radiation observed in the last 50 years in Poland.

4.2 Spatial variability of ET_o

The monthly and the growing season sums of ET_o, averaged over 35 years, characterise the spatial variability of the multi-year mean reference evapotranspiration. The minimum multi-year average ET_o in the growing season equals to 469 mm occured in the station no. 10, located in the south-western part of Poland. The maximum sum of ET_o, average in time, equals to 566 mm, was observed in the central part (the station no. 8).
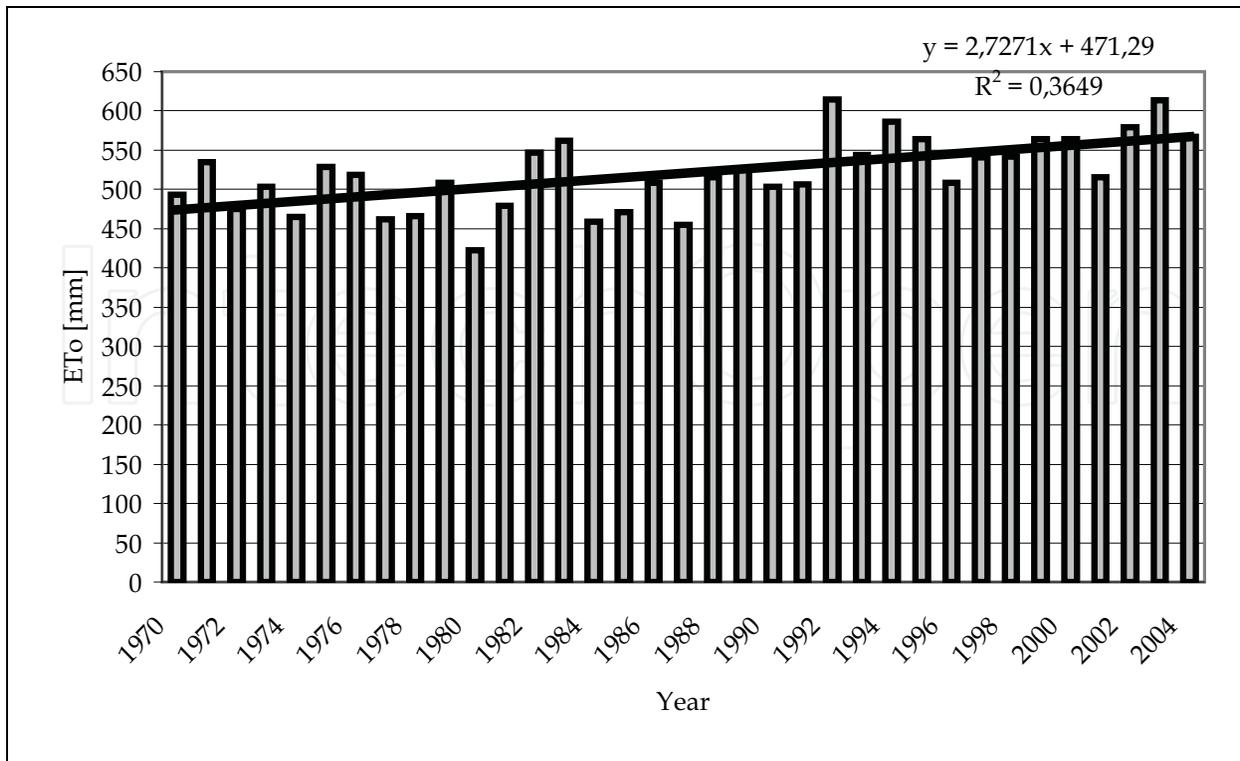
$$y = 2{,}7271x + 471{,}29$$
$$R^2 = 0{,}3649$$

Fig. 3. Sums of ET_o in the growing season (Apr-Sep) in 1970-2004, averaged over 40 stations

Similar to the spatially averaged ET_o (Tab. 2), the monthly sums of ET_o, averaged in time, were the highest in July (120 mm) in the central Poland and the lowest in September (45 mm) in the north-eastern part (Tab. 3).

The spatial variability of reference evapotranspiration (the variability coefficient 5-7%) was lower than the temporal variability. It means the bigger differentation of the reference evapotranspiration in the years than in the space.

Parameter	Period						
	Apr	May	June	July	Aug	Sep	Apr-Sep
Mean [mm]	61	97	104	110	96	54	520
Minimum [mm]	53	85	92	98	86	45	469
Maximum [mm]	66	105	113	120	107	62	566
Median [mm]	62	97	103	110	97	55	524
Standard deviation [mm]	3	5	6	6	6	4	28
Variability coefficient [%]	6	5	5	5	6	7	5

Table 3. Statistics of spatial variability of ET_o averaged over 35 years

The absolute minimum reference evapotranspiration sum in the growing season at all stations and in all years amounted to 366 mm and was determined in 1980 in the north-eastern part of Poland (station no. 2) (Tab. 4). The absolute maximum was 732 mm in 1982 in the central Poland (station no. 27).

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Period	Abs min	Abs max
April	31	105
May	46	138
June	67	161
July	62	180
August	51	161
September	30	168
April-September	366	732

Table 4. Absolute minimum and maximum sums of reference evapotranspiration ET_o [mm] at 40 stations in 1970-2004

The values of reference evapotranspiration determined for the probability of exceeding of 0.2, 0.5 and 0.8 can be referred to the conditions of warm and dry, average and cold and wet weather, respectively. The probability of 0.2 means that evapotranspiration can be higher than or equal to a given amount. Practically it means that evapotranspiration at the probability of 0.2 can be expected every five years, at the probability of 0.5 - every two years and at the probability of 0.8 - eight years in a decade.

A spatial differentiation of the reference evapotranspiration is observed in Poland (Fig. 4, 5, 6). The growing season sum of the reference evapotranspiration, calculated with the Penman-Monteith method, ranges in the area of the country from 480 to 560 mm in an average year (Fig. 4), 500 to 620 mm in a hot and dry year (Fig. 5) and 460 to 520 mm in cold and wet year (Fig. 6).
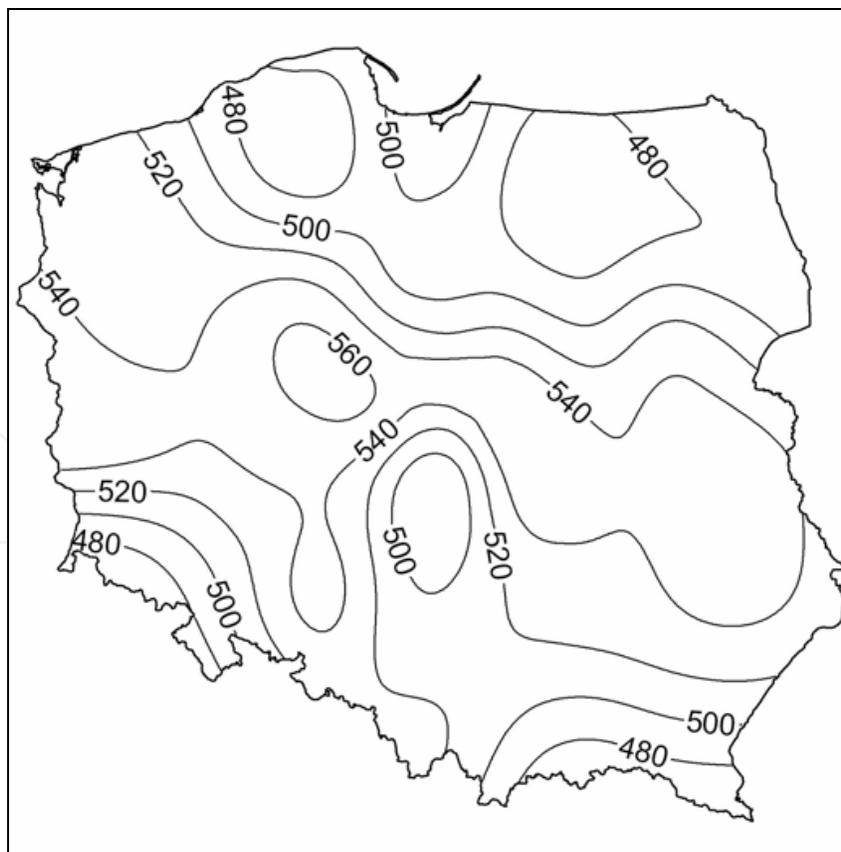

Fig. 4. Reference evapotranspiration ET_o [mm] in the growing season (Apr-Sep) at the probability 0.5
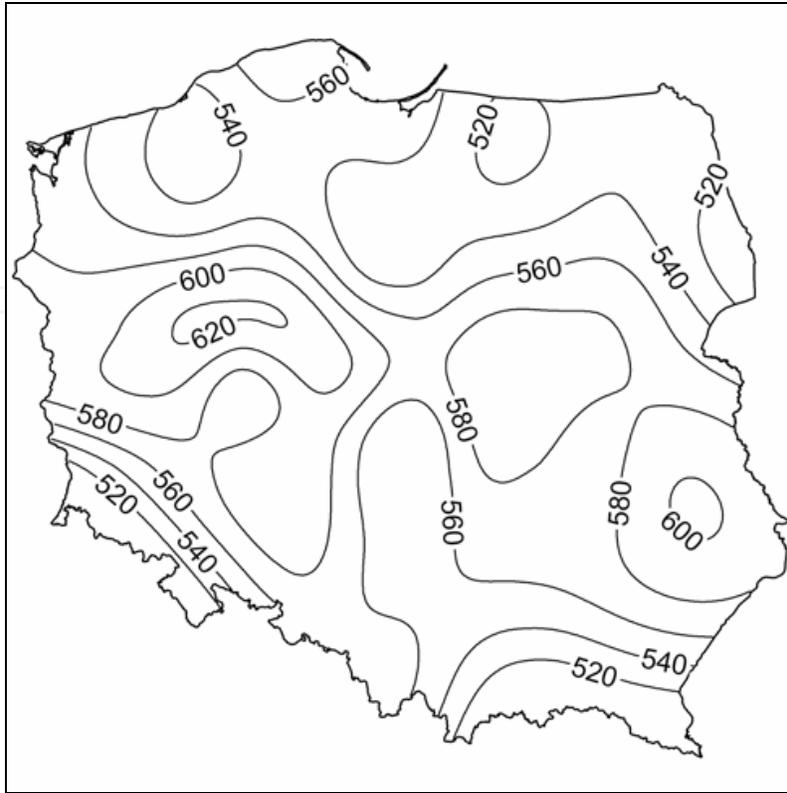
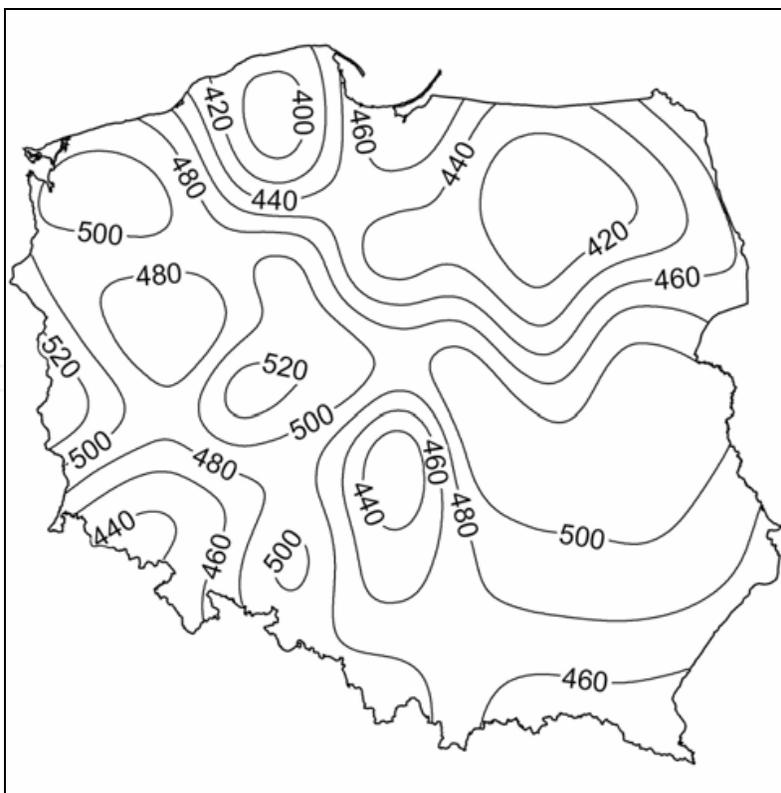Fig. 5. Reference evapotranspiration ET_o [mm] in the growing season (Apr-Sep) at the probability 0.2

Fig. 6. Reference evapotranspiration ET_o [mm] in the growing season (Apr-Sep) at the probability 0.8
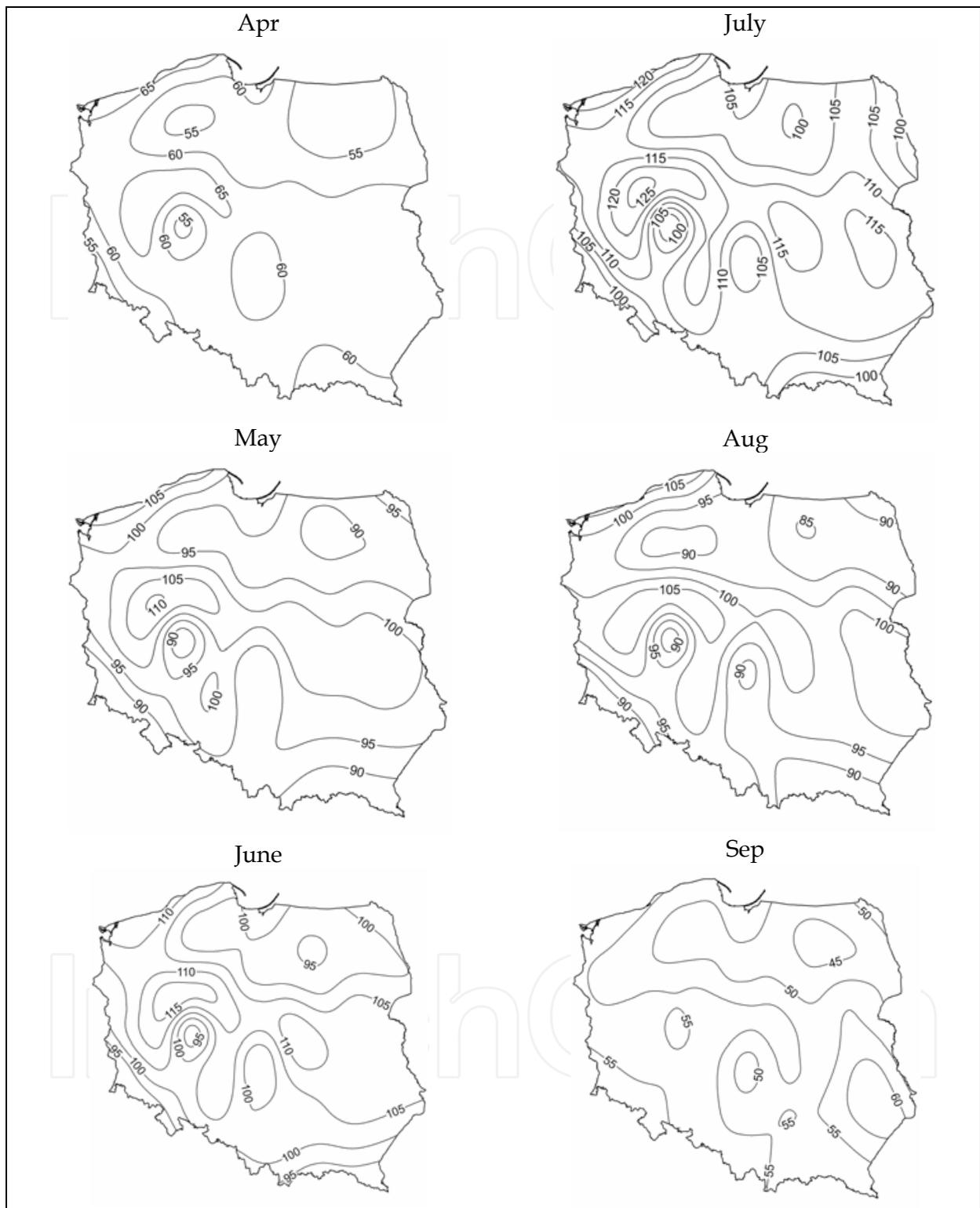
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Fig. 7. Mean monthly sums of reference evapotranspiration ET_o [mm]

Generally the higher reference evapotranspiration were recorded in central Poland from west to east. The highest values occurred in the small area with the stations nos. 4, 8, 11, 13, 15, 25 and 27. This is the driest region of Poland with the lowest rainfall which often is less than 300 mm in a year. The region is most threatened by meteorological droughts. In

connection with high reference evapotranspiration the region is threatened by agricultural droughts. Although no significant decrease in the annual precipitation is predicted in Central Europe due to global climate change, considering the forecasted increase in temperature, possible increase in reference evapotranspiration and water shortage is very likely in the future in that region.

Similar to the sum of the reference evapotranspiration in the growing season, the highest values of the monthly sums occurred in the mid-western part of Poland, reaching 125 mm in July in that region (Fig. 7). The lowest ET_o is observed in April and September, being less twice than in July.

5. Agro-climatic regions

According to the sums of reference evapotranspiration in the growing season the agro-climatic regions of Poland have been distinguished using cluster analysis. The *k*-means clustering algorithm has been applied for grouping the meteorological stations of similar reference evapotranspiration.

Cluster analysis is an exploratory data analysis tool which aims at sorting different objects into groups in a way that the degree of association between two objects is maximal if they belong to the same group and minimal otherwise. The *k*-means method is one of different clustering methods and it produces exactly *k* different clusters of the greatest possible distinction. The goal of the method is to minimize variability within clusters and maximize variability between clusters. The similarity rules apply maximally to the members of one cluster and minimally to members belonging to the rest of the clusters. The significance test evaluates the between group variability against the within-group variability when computing the significance test for the hypothesis that the means in the groups are different from each other. In *k*-means clustering, the algorithm moved stations in and out of groups (clusters) to get the most significant ANOVA results (Romesburg, 2004).

Taking into account the range of variability of ET_o in the area of Poland as well as the regionalization of climatic conditions, three clusters (*k* = 3) were determined *a priori*, that are to be as distinct as possible. The performed analysis showed very different means. The magnitude of the *F* value from the analysis of variance indicates a very significant discrimination between clusters (p<0.0000001).

The analysis allowed to classify reference evapotranspiration occurring in the area of Poland into the meaningful piles. On that basis the three agro-climatic regions can be distinguished in Poland:

A – with high reference evapotranspiration (high evaporative demand of the atmosphere),

B – with medium reference evapotranspiration (medium evaporative demand of the atmosphere),

C - with low reference evapotranspiration (low evaporative demand of the atmosphere).

The distinguished regions are shown in Fig. 8 and the values of ET_o in these regions in Tab. 5. Into the A region 14 stations were classified, into the B region - 14 and into the C region - 12. The mean ET_o in each region is calculated as the mean of all stations classified into the region. The maximum and minimum ET_o are the maximum and minimum multi-year (1970-2004) average values recorded at any station located in the region.

The A region is characterized by the spatially and temporally averaged reference evapotranspiration according to the Penman-Monteith method equal to 550 mm from April to September, the B region – 520 mm and the C region – 490 mm. It should be realized that

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ET_o in a give year and at a given station can be of the magnitude that matches another class (region). This should not be the base for changing the classification and the affiliation of a station to that class.
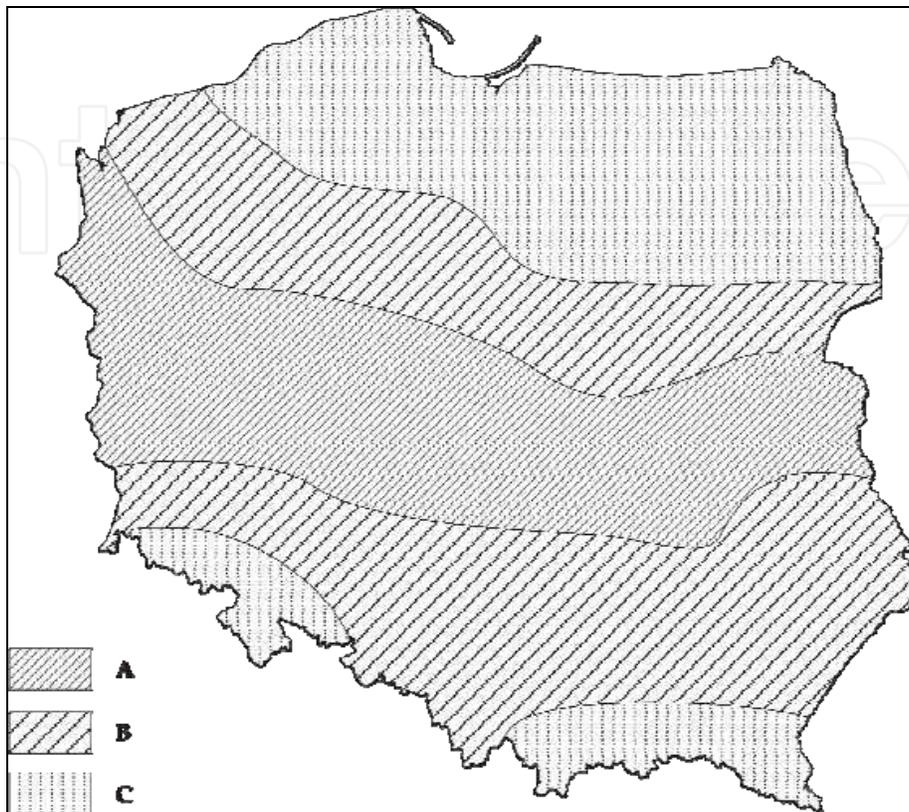

Fig. 8. Agro-climatic regions: A – high ET_o, B – medium ET_o, C – low ET_o

Parameter	Agro-climatic region		
	A	B	C
Class of ET_o	high	medium	low
Mean ET_o [mm]	550	520	490
Max ET_o [mm]	566	546	514
Min ET_o [mm]	536	489	469

Table 5. Reference evapotranspiration ET_o in the agro-climatic regions of Poland

6. Climatic water balance

Reference evapotranspiration can been applied to a wide variety of research problems in the field of agrometeorology and agricultural water management. Besides of the very popular method of calculating crop evapotranspiration and crop water use with crop factors, reference evapotraspiration can be used to compute the climatic water balance. The climatic water balance one can interpret as the indicator of climate dryness.

The climatic water balance CWB was calculated using the measured precipitation and the calculated ET_o at 40 stations and in 35 years (1970-2004). The spatial distribution of CWB (Fig. 9) shows its differentiation in Poland, depending on the agrometeorological conditions.

The mean multiannual values of this balance in the growing season (April to September) were negative at most examined stations. In the most part of the country reference evapotranspiration exceeds precipitation. The climatic water balance, averaged over all years and all stations, was equal to -144 mm in the growing season.

The higher positive values of CWB (0-100 mm) were found in the southern Poland, the region situated near the Karpaty mountains. Precipitation exceeds reference eapotranspiration in that region. In the north part of Poland – near the Baltyk sea and in the north-east part of the country the values of climatic water balance were negative but higher than –100 mm. The values of CWB less than –150 mm were in the central Poland, from west to east. The lowest values of the balance (less than –200 mm) were on the area from the north-west to the central part. The highest risk of agro-climatic water deficit can be expected in these regions.
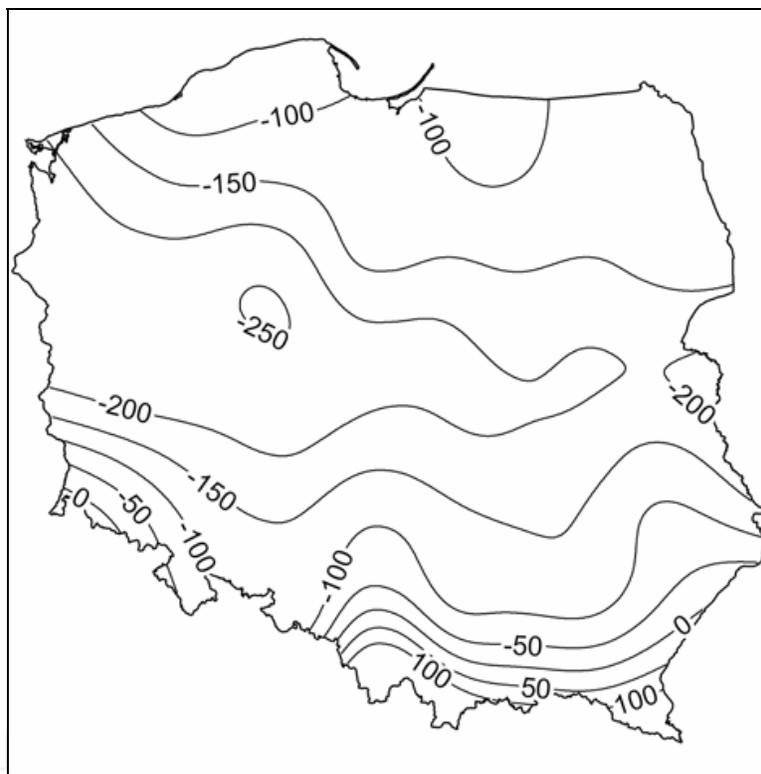
Fig. 9. Climatic water balance [mm] in the growing season (Apr–Sep), mean in 1970-2004

For the operational, real-time estimation of climatic water balance in different regions and to get the comparable evaluation of precipitation deficit or surplus, the standardized climatic water balance S-CWB can be used (Labedzki & Bak, 2004). After the performance of standardization one can analyse the actual situation at different stations and the evaluation of actual agro-climatic conditions is comparable. The standardized climatic water balance is an index indicating climatic water balance lower or higher than the mean value or the median if the probability distribution of climatic water balance is not normal. This method allows the CWB distribution at the station to be represented by a mathematical cumulative probability function. One can then tell what is the probability of CWB being less than or equal to a certain amount. The probability of CWB being less than or equal to the median is 0.5. The probability shows how often one can expect a particular value of CWB.

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To categorize and evaluate the deficit or surplus of precipitation in relation to reference evapotranspiration, CWB should be compared with the boundaries of different agro-climatic conditions classes. Following the example of the classification of the standardized precipitation index SPI (McKee et al., 1993; Paulo & Pereira, 2006; Vermes, 1998), seven classes can be distinguished (Tab. 6). Because S-CWB are standardized values, the threshold for particular classes corresponds to the definite probabilities of non-exceeding a given value. For example a threshold S-CWB for extremely dry period (S-CWB ≤ –2.0) corresponds to the climatic water balance (with the lower) with a probability of occurrence 2%. S-CWB = –1.0 corresponds to the climatic water balance (with the lower) with a probability of occurrence 16%.

Anyway S-CWB needs a careful interpretation. It is a relative index being the standardized deviation from the median and indicating climatic water balance lower or higher than the median for the period and location under consideration. In the S-CWB methodology the average climatic water balance is treated as normal, which often means water deficit for agriculture. This index characterises only climatic water deficit or surplus.

S-CWB	Agro-climatic conditions	Cumulative probability
≤ -2.00	extremely dry	0.0228
-1.99 to -1.50	very dry	0.0668
-1.49 to -1.00	moderately dry	0.1587
–0.99 to 1.00	normal	0.8413
0.99 to 1.50	moderately wet	0.9332
1.49 to 2.00	very wet	0.9772
> 2.0	extremely wet	1

Table 6. Classification of agro-climatic conditions according to standardized climatic water balance S-CWB

7. Conclusion

1. In this study the performance of the FAO Penman-Monteith method to estimate reference evapotranspiration under climatic conditions of Poland is presented. Using ten-day weather data from 40 weather stations from 1970-2004, the PM reference evapotranspiration was calculated. The analysis of temporal and spatial variability of the PM reference evapotranspiration was made. In addition, the reference evapotranspiration was used to determine the agro-climatic regions and climatic water balance in Poland.

2. The sum of reference evapotranspiration in the growing season from April to September exceeds 500 mm in most area of Poland. Averaged over 35 years and 40 stations it amounts to 520 mm. The monthly sums of reference evapotranspiration, averaged over 40 stations, ranges from 54 mm in September to 110 mm in July.

3. The spatial variability of reference evapotranspiration was lower than the temporal variability. It means the bigger differentation of the reference evapotranspiration among years than among stations.

4. As a general rule, reference evapotranspiration isolines as yielded by the Penman-Monteith method are traced almost west-east. They showed a characteristic pattern, by decreasing from the central part to the northern and southern part of Poland. The

highest reference evapotranspiration were recorded in the region with the lowest rainfall.

5. The spatial distribution of reference evapotranspitration in the area of Poland is similar to the spatial distribution of precipitation.

6. Using cluster analysis three agro-climatic regions were distinguished in Poland differing significantly in reference evapotranspiration.

7. The statistically significant increase in reference evapotranspiration was determined in 1970-2004 due to the increase in temperature.

8. In most of the country reference evapotranspiration exceeds precipitation and this is the reason of water shortage for crops. This tendency is expected to grow with the foreseen climate warming.

9. Future research will be addressed to further develop an operational system for assessing reference evapotranspiration with the FAO Penman-Monteith method and potential and actual evapotranspiration in a regional and the entire country scale. Future studies will consider the ability of forecasting reference evapotranspiration to forecast meteorological and agricultural droughts and to improve the management of irrigation systems. Of particular interest is which method of forecasting is better – based on synoptic and mezoscale models or statistical models.

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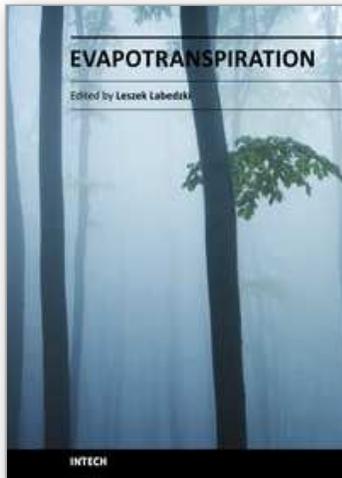
Evapotranspiration

Edited by Prof. Leszek Labedzki

Evapotranspiration is a very complex phenomenon, comprising different aspects and processes (hydrological, meteorological, physiological, soil, plant and others). Farmers, agriculture advisers, extension services, hydrologists, agrometeorologists, water management specialists and many others are facing the problem of evapotranspiration. This book is dedicated to further understanding of the evapotranspiration problems, presenting a broad body of experience, by reporting different views of the authors and the results of their studies. It covers aspects from understandings and concepts of evapotranspiration, through methodology of calculating and measuring, to applications in different fields, in which evapotranspiration is an important factor. The book will be of benefit to scientists, engineers and managers involved in problems related to meteorology, climatology, hydrology, geography, agronomy and agricultural water management. We hope they will find useful material in this collection of papers.

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