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EVAPORATION FROM WATER SURFACE AS CLIMATIC INDICATOR TO ESTIMATE MOUNTAIN GRASSLAND EVAPOTRANSPIRATION*

Andrzej Misztal, Jan Zarzycki

Department of Ecology, Climatology and Air Protection, University of Agriculture in Krakow
Al. Mickiewicza 24/28, 30-059 Kraków, Poland
e-mail: rmmiszta@cyf-kr.edu.pl

A b s t r a c t. This paper presents a study on the evaporation of water from the surface in the area of the Lesser Pieniny Mts., determined on the basis of measurements at the climatic-lysimetric station in Jaworki. The evaporation of water from the surface is diversified in specific 10-day periods and months of the vegetation season, and the total for April-September was 334.1 mm. The quantity of evaporating water was lower than the measured reference evapotranspiration, assumed to be the evaporation of a well-watered, compact grassy sward, and lower than the reference evapotranspiration calculated in accordance with the Penman formula in French modification and the Penman-Monteith formula. In the area of the Lesser Pieniny Mts., the evaporation of water can be expressed as a function of the deficit of air humidity and – to a lesser extent – of air temperature. The seasonal plant coefficients k_c determined on the basis of evaporation from open water surface E_w can be used successfully to determine the evapotranspiration of mountain grassland.

K e y w o r d s: water evaporation, reference evapotranspiration, climatic factors, seasonal plant coefficients

INTRODUCTION

Evaporation from water surface is an essential element of water balance in any drainage basin – along with transpiration, evaporation from the soil and areas not covered by vegetation. The amount of water which evaporates from the surface of open water depends chiefly on the evaporative powers of the atmosphere coming into contact with the water table. These powers are determined by mete-

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orological factors, and principally the following: the deficit of air humidity, air temperature, insolation, and wind velocity (Konopko 1976, Szajda 2001). The evaporation from the surface of open water is usually measured using evaporimeters placed at ground level. These measurements are easy to conduct in any habitat, and for this reason they are often used in comprehensive characterisation, as an indicator that fairly accurately describes the local climatic conditions that exist in various habitats (Hupet and Vanclooster 2001, Kay and Davies 2008, Misztal 1985, Szajda 1997). They are also applied as one of the elements that help to determine seasonal plant coefficients that have been used to estimate the actual evapotranspiration rate of wild or cultivated plants (Allen *et al*. 2005, Clothier *et al*. 1982, Szajda 1997, Szajda 2001a).

The aim of the study was to determine the value of evaporation from the surface of open water, in the Pieniny Mts. region, and its changes over time, as well as to prove that water evaporation is a good indicator for comprehensive characterisation of the local climatic conditions. Additionally, the study aimed to show that in the conditions prevailing in the region of the Pieniny Mts. the evaporation of water permits a relatively precise indirect determination of water demand of mountain grassland.

EXPERIMENTAL PROCEDURES – MATERIALS AND METHODS

The results presented in the article originate from the meteo-lysimeter station located in the Lesser Pieniny Mts., in the Grajcarek stream basin, at the altitude of about 600 m a.s.l., in te area of IMUZ Research Station in Jaworki. Measurements of water evaporation were conducted in 1974-1998 in a pan evaporimeter with the area of 0.2 m^2 and 0.5 m deep, placed flush with the ground covered by grass vegetation. Daily values of evaporation from the water surface were determined by means of a calibrated container enabling measurement of water level in the evaporimeter, every day at 7.00, during the period from the third decade of April until September. The station was also equipped with a Stevenson screen, in which standard measurements of meteorological factors were conducted according to the guidelines of the Institute of Meteorology and Water Management (IMGW). Decade values of slow evaporation of the water table were compiled also for wet and dry, and for cool and warm years. It was assumed, after Marcilonek *et al.* (1980), that precipitation totals during the vegetation period, with 20% and lower probability of occurrence, characterise dry years, whereas those when the probability was 80% and higher – wet years. If similar criteria are applied for the air temperatures, it was assumed that the temperatures total of 20% and lower probability of occurrence characterise cool years, whereas those when the probability is 80% and higher – warm years.

Evapotranspiration research on grassland sward used as a meadow (three cuts) were conducted during the discussed period at the lysimeter station and in the simulated pasture system (six time sward cutting). Diverse fertilisation was applied as a factor significantly diversifying yields. The evapotranspiration was also determined for grassland sward with constant height of about 12 cm.

The results obtained allowed also to determine the reference evapotranspiration using two methods: the Penman method, which includes aerodynamic factors and thermal balance, and the modified by Montheith (1965) Penman-Monteith method, additionally including standard parameters of roughness and surface resistance, which allows better estimation of the reference evapotranspiration and eliminates the problem of overestimation in calculations using the original Penman formula.

Statistical dependencies were described by means of regression equations. Correlation coefficients r and determination coefficient r^2 were calculated, as well as standard estimation errors (SEE) and values of statistical significance test (F_{obl}). The significance of the dependencies obtained was evaluated by comparing the coefficients and rates of correlation with critical values at the significance level $\alpha = 0.01$, the values of significance test F_{obl} with $F_{0.01}$ values, and by assessment of the value of determination coefficient r^2 evidencing the magnitude of dispersion error $s = 100 - r^2$. It was assumed that the dependence is significant if the calculated $r > r_{0.01,}$ $F_{obl} > F_{0.01}$ and the determination coefficient $r^2 > 50\%$.

The conformity assessment of real evapotranspiration value, computed using plant coefficients $k_c = ETr\ E_w^{-1}$, with the measured values was conducted using Relative Mean Square Error – CBK (Ozga-Zielińska, Nawalany 1979), a_0 and a_1 coefficients in regression relationship $ETr_{pom} = a_0 + a_1 ETr_{obl}$, correlation coefficients between ETr_{pom} and ETr_{obl}; histograms of residual values distribution ETr_{pom} and ETr_{obl}.

RESULTS

Evaporation from water surface

In the period of April-September, the evaporation of water at ground level, measured as averages for 10-day periods, ranged from 13.6 mm to 27.6 mm. In the 10-day periods, the evaporation measured in the particular years of the study was even more diversified (from 6.2 mm in September to 35.7 mm in June, July, and August). In the growing period, the average sum of evaporation from the water table in the studied region was equal to 334.1 mm, fluctuating in particular years from 287.1 to 363.9 mm. In dry years, the average evaporation of surface water in April-September period was 335.2 mm, whereas in the relatively wet years – 303.7 mm. The average evaporation from water surface in the warm years was 359.5 mm, and in the cold years – 317.4 mm (Tab. 1).

Table 1. Ten-day values of evapotranspiration from open water surface (E_w) during vegetation season in Jaworki region (mean in the years 1974-1998)

Month, ten-day period		E_w (mm) maximum	minimum	mean	SD	v (%)
IV	3	20.2	8.6	13.7	4.29	33.0
V	1	27.5	8.0	18.3	5.10	28.7
	2	29.8	9.7	19.5	5.52	29.0
	3	29.3	12.5	20.8	4.50	22.2
	total	68.4	38.8	58.6	9.74	16.6
VI	1	35.0	18.4	25.1	4.79	19.6
	2	32.6	15.4	23.3	3.90	17.2
	3	35.7	16.9	23.5	5.71	24.9
	total	89.0	53.7	72.0	9.19	12.8
VII	1	31.3	16.1	23.1	4.25	18.9
	2	30.5	14.5	21.5	4.20	20.1
	3	35.7	22.3	27.6	4.29	16.0
	total	88.1	57.5	72.2	8.15	11.3
VIII	1	35.7	15.2	24.3	4.49	18.9
	2	32.3	17.2	24.0	4.00	17.1
	3	26.3	17.1	21.9	3.04	14.3
	total	85.6	55.2	70.3	8.74	12.5
IX	1	26.8	11.9	18.7	3.84	21.1
	2	23.9	6.2	15.0	4.31	29.6
	3	20.1	7.7	13.6	3.54	26.7
	total	58.6	38.5	47.3	5.85	12.4
in the period April-September	mean	363.9	287.1	334.1	27.63	8.3
	in the years dry	363.4	315.2	335.2	25.47	7.6
	in the years moist	321.5	295.0	303.7	17.68	5.8
	in the years warm	363.9	354.2	359.5	4.67	1.3
	in the years cool	348.1	292.7	317.4	28.18	8.9

Explanations: SD – standard deviation, mm; v – variability coefficient

Relationship between water evaporation and meteorological factors

The diversity in the quantity of water evaporating from the surface in dry, wet, warm, and cold years indicates the impact of the climatic conditions on the course of this process. The relationship between E_w and the deficit of air humidity (d) in the conditions prevailing during the study is illustrated by a regression equation:

$$E_w = 1.133\ d^{0.476} \qquad r = 0.773 \qquad (1)$$

Looking for statistical relationships between water evaporation and air temperature (t), it appeared that this relationship can be best described by the following regression equation:

$$E_w = 0.389\ t^{0.664} \qquad r = 0.677 \qquad (2)$$

The relationship between water evaporation and sunshine (*U*) was the least significant. In the regression equation describing it:

$$E_w = 1.368\ U^{0.283} \qquad r = 0.473 \qquad (3)$$

only 21% of the variability in water evaporation was caused by the effect of sunshine.

The simultaneous inclusion in the equation of both air humidity deficit and air temperature did not contribute in any marked way to the increase in the significance of the relationship, whose statistical description is presented by the regression equation given below:

$$E_w = 1.699\ d + 1.097t \qquad r = 0.612 \qquad (4)$$

Therefore, the air humidity deficit appears to be the best indicator permitting the most probable determination of evaporation from open water surface (E_w) in the conditions prevailing during the study.

Comparison of water evaporation and reference evapotranspiration

The basic methodological difficulty in determining evapotranspiration using empirical formulae estimating evaporation as a function of climate and crop factor results from the complicated effect of various factors on the evaporation process. Thornthaite's formula (basing solely on air temperature value) is one of the better known empirical formulae worldwide. Penman's method has been also widely used (Burman *et al*. 1983). It has undergone numerous modifications, of which Monteith's modification has won wide recognition (Allen *et al*. 1998). Doorenbos and Pruitt modified Penman's formula introducing *k* plant coefficient dependent of the kind of plant and soil use (Allen *et al*. 2005). It has become the most commonly applied method of calculating evapotranspiration, recommended by FAO and ICID.

When evapotranspiration is calculated for plants sufficiently supplied with water, a two-stage method is recommended, using a plant coefficient characteristic for a given plant (Allen *et al*. 1998). More often than not, it is the evapotranspiration of an actively developing, well-watered grassy sward, fully covering soil, with a permanent height of 12 cm, that is being used to calculate the actual level of evapotranspiration. In the mountain grassland described here, the evapotranspiration of such a grassy sward had ten-day values ranging from 10.4 to 39.5 mm, and its sum for the vegetation season was 347.5 mm.

In the area of the Lesser Pieniny Mts., the changes in multi-year average values for ten-day periods of water evaporation and reference evaporation, calculated according to Penman's formula in French modification, and the Penman-Monteith formula, are illustrated in Fig. 1.

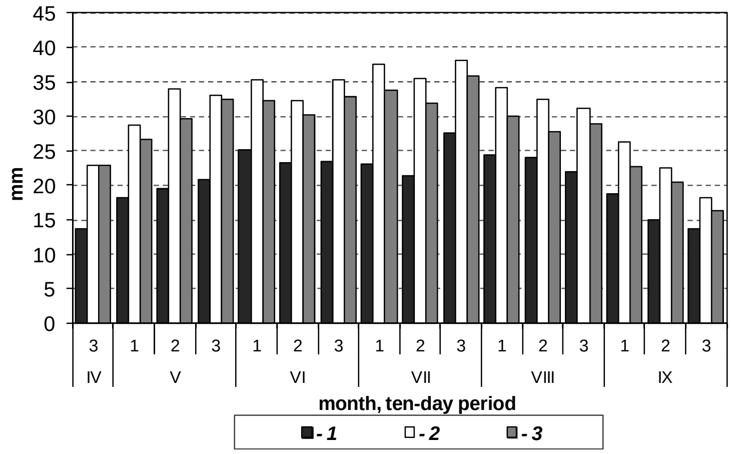

Fig. 1. Totals of ten-day water evaporation (1), reference evapotranspiration calculed using French modified Penman equation (2) and Penman-Monteith (3) at Jaworki (mean in the years 1974-1998)

This definitely shows lower amounts of water evaporation than the reference evaporation in all ten-day cycles of the studied period, and indicates significant differences in the ten-day total values of reference evapotranspiration calculated using both formulas. The statistical comparison of the results obtained, carried out using linear regression, proves – with high probability – that this relationship can be described by the following formula (Misztal 2000):

$$\mathrm{ET}_{o\ Pen-Mont.} = 0.89\ \mathrm{ET}_{o\ Pen-Fran.} \qquad r = 0.868 \qquad (5)$$

The analysis, based on the collected data, of the relationship between 10-day values of evaporation from the surface of open water and the reference evapotranspiration calculated in accordance with the methods mentioned earlier, shows that this relationship is statistically significant (Tab. 2).

Table 2. Parameters and statistical characteristics of regression dependency between water evaporation from ground surface E*w* and reference evapotraspration ET*o*

Parameter	ET*o* calculated using						Evapotranspiration from sward 12 cm high		
	French modified Penman			Penman-Monteith					
	value	p	SE	value	p	SE	value	p	SE
a_0	0.809	0.756	2.549	1.791	0.548	2.909	–0.556	0.450	1.368
a_1	0.645	< 0.001	0.806	0.671	< 0.001	0.101	0.926	< 0.001	0.054
r	0.905	< 0.001	0.113	0.872	< 0.001	0.131	0.862	< 0.001	0.053
r^2 (%)	82			76			74.3		
$F_{calc.}$	64.07	< 0.001		44.49	< 0.001		251.02	< 0.001	
SEE	1.815			2.097			3.115		

Explanations: a_0, a_1 – parameters of the equation $Ew = a_0 + a_1\ ETo$, r – correlation coefficient, r^2 – determination coefficient, p – level of significance, $F_{calc.}$ – statistical significance test of tested factor share in regression model, SE – standard error of parameter, SEE – standard error of estimation

In the case of reference evapotranspiration calculated using Penman's formula in French modification, this relationship can be described by the regression equation in the following form:

$$\mathrm{E}_w = 0.89 + 0.645\ \mathrm{ET}_{o\ Pen-Fran.} \qquad \mathrm{r} = 0.905 \tag{6}$$

whereas, when calculating reference evapotranspiration using the Penman-Monteith method, the relationship assumes the following form:

$$\mathrm{E}_w = 1.791 + 0.926\ \mathrm{ET}_{o\ Pen-Mont} \qquad \mathrm{r} = 0.872 \tag{7}$$

Similarly, as the reference evapotranspiration can be calculated using the Penman formula, so can the evapotranspiration of grassy sward, 12 cm in height, be correlated with the course of evaporation of water from the surface (Tab. 2). The regression equation describing this relationship has the following form:

$$\mathrm{E}_w = -0.556 + 0.645\ \mathrm{ET}_{sward} \qquad \mathrm{r} = 0.862 \tag{8}$$

Seasonal plant coefficients used to calculate actual evapotranspiration

The numerical data collected during the measurements taken in the Lesser Pieniny Mts. permitted the determination of such coefficients for mountain grassland (Tab. 3). The analysis of the regression equations parameters between measured and calculated values of evapotranspiration, in meadow and pasture, shows that their conformity is high for both habitats. That is confirmed by conformity measures obtained (at α = 0.01) for measured and calculated evapotranspiration: r, F_{calc}, and CBK (Tab. 4).

Table 3. Decade crop coefficients $k_{c,} = ET\ E_w^{-1}$ for meadow and pasture depending on the amount of assumed yield

Month	Ten-day period	Meadow			Pasture	
		yield (t ha $^{-1}$)				
		< 6	6-10	> 10	< 4	> 4
IV	3	1.13	1.20	1.31	1.08	1.13
	1	1.35	1.44	1.57	1.27	1.34
V	2	1.81	1.98	2.07	1.11	1.22
	3	2.01	2.12	2.20	1.54	1.63
	1	1.09	1.17	1.29	1.09	1.20
VI	2	1.32	1.39	1.46	1.30	1.34
	3	1.61	1.68	1.75	1.39	1.48
	1	1.86	1.91	1.97	1.13	1.21
VII	2	1.98	2.09	2.14	1.48	1.57
	3	1.18	1.22	1.29	1.58	1.68
	1	1.27	1.32	1.38	1.10	1.22
VIII	2	1.46	1.49	1.53	1.24	1.33
	3	1.58	1.61	1.67	1.38	1.42
	1	1.66	1.72	1.77	1.06	1.26
IX	2	1.71	1.79	1.86	1.31	1.42
	3	1.76	1.82	1.91	1.39	1.49

Table 4. Parameters and statistical measures of conformance of evapotraspiration $Etr_{calc.}$ measured in lysimeters and $Etr_{meas.}$ computed using k_c = Etr/Ew coefficient for dry-ground grasslands

Parameter	Meadow			Pasture		
	value	p	SE	value	p	SE
a_0	1.553	< 0.357	1.678	1.923	< 0.095	1.141
a_1	0.938	< 0.001	0.046	0.946	< 0.001	0.042
r	0.901	< 0.001	0.044	0.912	< 0.001	0.040
r^2 (%)	81.2			83.2		
$F_{calc.}$	417.96	< 0.001		509.25	< 0.001	
SEE	3.331			2.918		
CBK	0.094			0.106		

Explanations: a_0, a_1 – parameters of the equation $ETr_{meas} = a_0 + a_1\ ETr_{calc}$, r – correlation coefficient, r^2 – determination coefficient, p – level of significance, $F_{calc.}$ – statistical significance test of tested factor share in regression model, SE – standard error of parameter, SEE – standard error of estimation, CBK – mean relative square error

On one hand, the negative asymmetry in the frequency distribution of residual values between the sums of evapotranspiration – measured ETr_{meas} and calculated ETr_{calc} – for meadow shows that the value of the calculated evapotranspiration is reduced in comparison to the measured value. On the other hand, the frequency distribution of residual values between the measured and calculated evapotranspiration for pasture shows that the values of calculated ETr are somewhat inflated in comparison to the measured values (Fig. 2). This figure implies also that in the case of meadow, 53% of residual values obtained as a result of calculations fall within the range of −2.0 to +2.0 mm 10 days^{-1}. In the case of pasture, however, 56% of residual values fall within the range of −2.0 to +2.0 mm 10 days^{-1}.

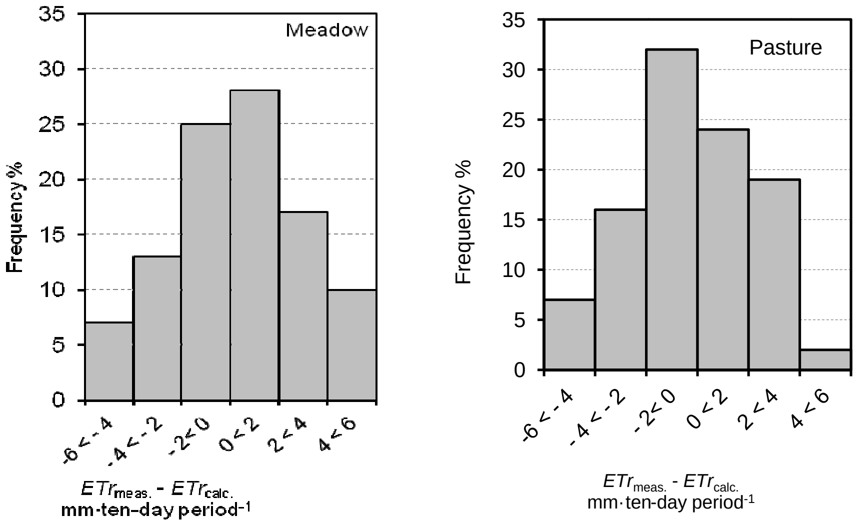

Fig. 2. Frequency histograms of residual values between measured and calculated evapotranspiration for meadow and pasture – measured ETr $_{meas.}$ and calculed ETr$_{calc}$

DISCUSSION

The amount of water evaporating from free surface in the Lesser Pieniny Mts. region is diversified in decades and months, but also in individual years. On average, in the period of April-September the value of evaporation from free water surface was 334.1mm. Under the conditions of the research, water evaporation proved to be significantly dependent on some meteorological factors measured in the same habitat. The best climate indicator allowing to determine E_w turned out to be vapour pressure deficit, resulting from the fact that it is a complex climate element indirectly depending also on air temperature and sunshine. Significant relationships between evaporation from open water surface and air vapour pressure deficit were mentioned in papers by Allen *et al*. 1998, Szajda 1997, 2001a. Also Roguski *et al*. (2002), who analysed the usefulness of selected formulae for computing reference evaporation for determining water requirements of grassland, revealed that water evaporation is an indicator better suited to local conditions than reference evaporation based on solar radiation computed by means of the Penman formula which, in their opinion, is little diversified spatially.

Evaporation from free water table proved to be an indicator which can be used for determining the evaporation power of the atmosphere, especially as the conducted research revealed statistically significant relationships between water evaporation and reference evaporation computed by means of the Penman method in French modification, and by the Penman-Monteith method, as has been corroborated also by the results of studies conducted by de Bruin 2000, Szajda 1997.

Studies on the course of evapotranspiration and field water use by various crops are complicated, therefore attempts have been made for a long time to determine the value of this phenomenon using indirect methods, in which the measure of the effect of meteorological factors is the reference evapotranspiration (ETo) computed by means of physical-empirical formulae using meteorological data. Evapotranspiration of various crops, using referential evapotranspiration, computed according to mathematical formulae is determined by means of commonly used seasonal crop coefficients k. The issue of real evapotranspiration assessment was addressed in many papers, among which works by Allen *et al*. 2005, Benli *et al*. 2006, Suleiman *et al*. 2007, Yarami *et al*. 2011 can be mentioned.

In the Lesser Pieniny Mts. region, evaporation from the water surface proved to be a good indicator to determine water requirements of grassland communities. A high compatibility was registered between evapotranspiration measured in dry meadow habitats and computed using seasonal crop coefficients $k_c = \frac{ETr}{E_w}$. Satisfactory results of evapotranspiration calculation using seasonal crop coefficients k_c determined for a meadow and pasture show that the results obtained may be successfully applied in practice to determine or forecast the real evapotranspiration of mountain grassland, as described in papers by Allan *et al*. 1998, Suleiman *et al*. 2007. They assume diversified values in individual months of the vegetation season and depending on forecasted amount of yield, as evidenced by research conducted, among others, by Eitzinger *et al*. 2002, Hunt *et al*. 2008, Łabędzki and Kasperska 1994, Oudin *et al*. 2010, Roguski and Łabędzki 1988, Rojek and Wiercioch 1990.

CONCLUSIONS

The analysis of the data on evaporation from the open water table, collected in the Jaworki area, permits the following conclusions to be drawn:

1. The evaporation of water measured in the region of the Lesser Pieniny Mts., using an evaporimeter at ground level, in the vegetation season attains ca. 334 mm. In particular 10-day periods during the vegetation season it is very diverse and can attain values between 6.2 and 35.7 mm.

2. In the whole of the vegetation season, the quantities of water evaporating from open water surfaces in the Jaworki area are lower than the reference evapotranspiration calculated according to both the Penman formula in French modification and the Penman-Monteith formula, and also lower than the evapotranspiration of well-watered compact grassy sward with a permanent height of 12 cm.

3. Evaporation from the surface of open water in the region of the Lesser Pieniny Mts. was dependent on the deficit of air humidity and – to a lesser degree – on air temperature.

4. Evaporation from the surface of open water is an indicator permitting a relatively precise determination of plants' demand for water. Among the benefits of this indicator one can mention the ease of taking measurements and the fact that its values depend on basic meteorological factors.

5. In order to calculate the evapotranspiration of grassland communities in the mountain grasslands within the region of the Lesser Pieniny Mts., the seasonal plant coefficients $k_c = \frac{ETr}{E_w}$ can be used successfully.

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PAROWANIE WODY JAKO KLIMATYCZNY WSKAŹNIK OCENY EWAPOTRANSPIRACJI GÓRSKICH UŻYTKÓW ZIELONYCH

Andrzej Misztal, Jan Zarzycki

Katedra Ekologii, Klimatologii i Ochrony Powietrza, Uniwersytet Rolniczy
Al. Mickiewicza 24/28, 30-059 Kraków
e-mail: rmmiszta@cyf-kr.edu.pl

S t r e s z c z e n i e. W pracy omówiono parowanie z powierzchni wody w rejonie Małych Pienin, określone na podstawie pomiarów w stacji klimatyczno-lizymetrycznej w Jaworkach. Parowanie z powierzchni wody było zróżnicowane w poszczególnych dekadach i miesiącach okresu wegetacyjnego, a jego średnia z wielolecia 1974-1998 suma w okresie kwiecień-wrzesień wyniosła 334,1 mm. Ilość parującej wody była mniejsza od pomierzonej ewapotranspiracji wskaźnikowej za jaką uznano parowanie dobrze zaopatrzonej w wodę zwartej runi trawiastej oraz od ewapotranspiracji wskaźnikowej obliczonej według formuły Penmana w modyfikacji francuskiej i Penmana-Monteitha. W rejonie Małych Pienin parowanie z otwartej powierzchni wody można wyrazić jako funkcję niedosytu wilgotności powietrza oraz w mniejszym stopniu temperatury powietrza. Określone w oparciu o wartości ewapotranspiracji z otwartej powierzchni wody E_w sezonowe współczynniki roślinne k_c mogą z powodzeniem służyć do wyznaczania ewapotranspiracji górskich zbiorowisk trawiastych.

S ł o w a k l u c z o w e: parowanie wody, ewapotranspiracja wskaźnikowa, czynniki klimatyczne, sezonowe współczynniki roślinne