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ON THE METHOD OF DETERMINING THE CLIMATIC WATER BALANCE IN MOUNTAINOUS AREAS, WITH AN EXAMPLE FROM THE POLISH CARPATHIANS

Abstract: The basis of the climatic assessment of the water resources of a given area should be formed by an index accounting for real precipitation and evaporation, i.e. the climatic water balance. In this paper, an attempt has been made at developing a method for determining the total evaporation, a basic element of the climatic water balance. The method is based on easily accessible meteorological data, can be verified in the natural conditions of the Polish Carpathians, and is simple, easy, and potentially capable of generating reliable results. Spatial representation of the results so generated was another objective of this study. This goal was accomplished through the use of the cartographic presentation, in the form of the 1:300 000 scale maps of semi-annual and monthly sums of the index of total evaporation and climatic water balance, for the western part of the Polish Carpathians.

Key words: standard and real precipitation, total evaporation, deficit of runoff, climatic water balance, precipitation deficits and excesses.

1. Introduction

The rise in water consumption connected with economic development and contemporary trends in climate changes has created the need for a detailed assessment of the actual water resources. Obtaining information about the magnitude and temporal distribution of the surface runoff, and about the formation of deep water resources, especially in mountainous regions, is difficult due to the limited number of recording stations. One possible method of determining the actual water resources is based on utilising climatic data. It should include two factors: input in the form of precipitation, and losses during evaporation.

The idea of focusing on the difference between precipitation (P) and evaporation (E) in order to characterise the degree of wetness of the areas, was applied for the first time in Poland by Schmuck (1952). The definition and the term climatic water balance (P-E) were introduced to both the scientific literature and engineering practice by

Bac (1974). That index, in various forms (standard or real precipitation, evaporation from open water surfaces or potential evaporation) has been used in the studies of many authors until the present day.

In the latest studies both in Poland (Rojek and Wiercioch 1995) and abroad (Tomlain 1993), all researchers have considered it necessary to use standard sums of precipitation. The analysis of the maps of the climatic water balance from such a perspective has revealed the possibility of using that index for the regional characterisation of atmospheric drought in Poland (Susze… 1995).

However, in utilising climatic water balances for the assessment of precipitation deficits and excesses, one should correct their quantitative values by accounting for total evaporation, i.e. the actual losses of water from the ground to the atmosphere. Consequently, the assessment of the moisture degree of the Polish Carpathians has been carried out, based on the value of the climatic water balance, i.e. the difference between the standard sums of precipitation (P) and the index of total evaporation ($E`_o$). The developed method may be used for determining and predicting the magnitude of total evaporation (the actual evapotranspiration) in the Polish Carpathians. This is of particular significance for agriculture when assessing precipitation deficits and excesses, since the positive values of the P-$E`_o$ index (when connected with the soil water content, relevant for plant life) may indicate excess precipitation in a given area, while the negative values may indicate precipitation deficits. Moreover, from this point of view, the climatic water balance may be the basis on which to assess water resources (runoff) from the climatic data, when hydrological data (especially in the case of uncontrolled catchment areas) are absent.

2. The objective of the study

From the perspective of the analysed topic, the choice of the appropriate method for determining the magnitude of evaporation is of fundamental importance, since this quantity should represent the actual loss of water from the ground to the atmosphere. Therefore, it is an especially important task to develop a method for determining the rate of total evaporation (actual evapotranspiration), which is a basic element of the climatic water balance. The method should be based on easily accessible meteorological data, should be verified in the natural conditions of the Polish Carpathians, and be simple, easy, and potentially capable of generating reliable results. Since the empirical formulae of Penman (French modification), and of Turc and Bac (Sarnacka et al. 1983, Turc 1964, Bac 1970) used in this paper, are frequently applied both in Poland and abroad, it has opened the possibility of testing the appropriateness of their use in the mountainous areas.

The spatial presentation of the obtained results was another, equally important objective of the study. This goal was accomplished through the use of the cartographic presentation in the form of the 1:300 000 scale maps of semi-annual and monthly sums of the index of total evaporation and climatic water balance, for the western part of the Polish Carpathians (Kowanetz 1998). One should emphasise that the most frequently encountered methods used in the studies published to-date, are maps of the climatic water balance and evaporation constructed by geometric interpolation. They account for, although only in an approximate way, the influence of the terrain and altitude on variation of the studied indices. Consequently, these studies do not deal with mountainous areas at all (and with the Carpathian catchment areas in particular) or only provide a very rudimentary approach.

3. Source material

The study is based on the observational data from three catchment areas: Skawa (up to the Wadowice water-gauge), Raba (up to the Proszówki water-gauge) and Dunajec (up to the Nowy Targ – Kowaniec water-gauge), all located in the western part of the Polish Carpathians (Fig. 1). The results of the measurements taken between 1951-1960, during the summer half-year (May-October), at 25 meteorological stations located approximately along the 20°E meridian, at elevations from 200 m to 2000 m, have been used. In addition, meteorological measurements from 8 stations during the 20-year period 1951-1970 have also been utilised (Tab. 1). For comparative purposes, data from the 30-year period 1961-1990 (climatological normal – „clino") have been collected from three stations (Kraków, Zakopane and Kasprowy Wierch).

The measurement data include mean daily and monthly values of the following meteorological variables: air temperature, water-vapour pressure, water saturation deficit, wind speed, insolation, cloudiness, and precipitation. The characteristics of the raw water balance for the studied water-gauge catchment areas (precipitation, runoff, deficit of runoff) during the summer half-years between 1951-1960, are taken from the publication entitled *Synteza surowego bilansu wodnego Polski w latach 1951-1965* (The synthesis of the raw water balance of Poland in the years 1951-1965, 1971) and for the period 1951-1970 are taken from the *Atlas Hydrologiczny Polski* (Hydrological Atlas of Poland, 1986).

Due to the lack of the measurements of total radiation in the studied area, which is necessary for the computation of the analysed evaporation indices, those values have been determined for particular locations from Black's formula, adopted for Poland by Podogrocki (1978). The albedo was assumed as a constant value of 0.20. This represents an average value, in agreement with the results obtained by Olecki (1989), for the area of the upper Vistula river basin during the vegetation season. Values of the potential evapotranspiration have been computed for the conditions of low-mown grass. It was assumed that grass height in meteorological gardens was more or less constant at about 10 cm, with the ground roughness parameter z_o = 0.01 m.

Comparisons of the meteorological and hydrological data for the periods between 1951-1960 and 1951-1970 did not reveal statistically significant differences between them. In spite of the fact that the 20-year period between 1951-1970 was characterised by a gradual increase in the flow (with the 5-year period 1951-1955 being the driest, and the 5-year period between 1966-1970 markedly rich in water – Stachy et al. 1979), the average meteorological and hydrological characteristics (precipitation, runoff) during this period did not differ significantly from the multi-annual period between 1961-1990 (which is considered by the climatologists to be a normal period in the

Fig. 1. The distribution of meteorological stations and water-gauging stations in the Polish Carpathians, with the physico-geographic regions according to Czeppe and German (1979, 1988) and Kondracki (1994). The characteristics of the stations indicated by numbers are given in Table 1.

Ryc. 1. Rozmieszczenie stacji meteorologicznych i posterunków wodowskazowych w Karpatach Polskich na tle regionów fizycznogeograficznych - wg Czeppego i German (1979, 1988) oraz Kondrackiego (1994). Liczby przy stacjach oznaczają numery stacji, których charakterystyki zamieszczone zostały w tabeli 1.

Tab. 1. The list of meteorological stations.

Tab. 1. Spis stacji meteorologicznych.

Station *Stacja*	H_s *(m)*	φ	λ	*Catchment area* *Zlewnia*	*Form of terrain* *Forma terenu*
1. Bochnia Chodenice*	200	49°59’	20°24’	Raba	concave
2. Kraków Obs.Astr.U J*	221	50°04’	19°57’	Wisła	convex
3. Wieliczka	225	50°00’	20°03’	Wisła	concave
4. Myślenice	295	49°49’	19°56’	Raba	concave
5. Maków Podhalański	350	49°44’	19°40’	Skawa	concave
6. Mszana Dolna	410	49°40’	20°05’	Raba	concave
7. Rabka*	510	49°36’	19°58’	Raba	convex
8. Raba Wyżna	600	49°34’	19°53’	Raba	convex
9. Nowy Targ*	600	49°29’	20°02’	Dunajec	concave
10. Czarny Dunajec	680	49°27’	19°51’	Dunajec	concave
11. Rdzawka	800	49°33’	19°58’	Raba	convex
12. Poronin	800	49°20’	20°02’	Dunajec	concave
13. Witów	835	49°20’	19°50’	Dunajec	concave
14. Zakopane*	844	49°18’	19°58’	Dunajec	concave
15. Bukowina Tatrzańska	880	49°21’	20°07’	Dunajec	convex
16. Łysa Polana	998	49°16’	20°07’	Dunajec	concave
17. Gubałówka*	1000	49°18’	19°56’	Dunajec	convex
18. Kuźnice	1023	49°16’	19°59’	Dunajec	concave
19. Luboń Wielki	1025	49°39’	19°59’	Raba	convex
20. Hala Ornak	1110	49°14’	19°51’	Dunajec	concave
21. Markowe Szczawiny	1180	49°35’	19°31’	Skawa	convex
22. Myślenickie Turnie	1360	49°15’	19°59’	Dunajec	convex
23. Morskie Oko	1400	49°12’	20°04’	Dunajec	concave
24. Hala Gąsienicowa*	1520	49°15’	20°00’	Dunajec	convex
25. Kasprowy Wierch*	1991	49°14’	19°59’	Dunajec	convex

* data 1951-1970 * dane z lat 1951-1970

study of climate). One may conclude then, that the base 10-year period (1951-1960, with data from 25 meteorological stations) adopted in this study, is sufficient for the analysis of spatial and dynamic climatic variation in the water balance of the studied area. One should also emphasise the fact, that data from a large number of meteorological stations in the Polish Carpathians were available only for the period between 1951-1960, since after 1960, many stations ceased to conduct measurements of air humidity with the August psychrometer, or the stations themselves were closed.

4. Methods

Adopting the appropriate assessment method of the magnitude of evaporation-related water loss in a given area, constitutes the critical issue in determining the climatic water balance. Information about total evaporation for the Polish Carpathians is rare and fragmentary in the scientific literature. Due to the fact that there is not a sufficient amount of data from direct measurements of evaporation, in order to attain the objective of this study one must resort to the use of the empirically derived formulae.

It is very difficult to determine the amount of total evaporation (actual evapotranspiration) only from meteorological data. During some phenological phases, the biological rhythm of the growth and development of vegetation exerts a greater influence on the amount of evapotranspiration than do the atmospheric conditions. The influence of non-meteorological factors may be expressed quantitatively, assuming that total evaporation (actual evapotranspiration) is affected by the same meteorological variables as are: physical evaporation, soil conditions and biological factors. Values of correction coefficients may be obtained through the use of one of the indicators of the evaporation process (potential evapotranspiration, indicatory evaporation) and then by conducting verification through comparisons with the data from the raw water balance – deficit of runoff.

The needs of research and engineering practice led to the development of a large number of formulae which have enabled indirect quantitative assessment of the evaporation. Such methods have primarily been developed for the lowland areas and have never been used in the areas of diversified terrain. In this study, the choice of the methods was influenced by the conformity of the evaporation distribution with the hypsometry of the terrain and the physiographic regions, by the availability and reliability of the basic data, and by the possibility of reconciling the theoretical assumptions of the evaporation process with the formulation of the equation. An attempt has been made at utilising the Penman empirical formula (French modification), the Turc formula for the potential evapotranspiration, and the Bac formula for the indicatory evaporation. In addition, the choice of the equation was influenced by the possibility of adapting it to various conditions through the application of the previously-developed correction coefficients or variable parameters dependent on the geographical location, by the FAO recommendations concerning the applicability of the formulae in planning and design work (the Penman method), and by their frequent use in practical applications (which implied that their absence in the study would be treated as an unexpected omission).

The equation for the potential evapotranspiration according to Penman (French modification) has the form (Sarnacka et al. 1983):

$$E_P = N\left\{\begin{array}{l}\left[G_0(1-\alpha)\left(0{,}209+0{,}565\dfrac{S}{S_0}\right)-\sigma T_A^{\,4}\left(0{,}56-0{,}08\sqrt{e}\right)\left(0{,}10+0{,}90\dfrac{S}{S_0}\right)\right]\cdot \\ \cdot\dfrac{1}{59}\dfrac{\Delta}{\Delta+0{,}65}+0{,}26(e_w-e)(1+0{,}4v)\dfrac{0{,}65}{\Delta+0{,}65}\end{array}\right\}$$

where:

E_p – the monthly sum of the potential evapotranspiration according to Penman [mm month^{-1}],

N – number of days in a month,

G_0 – daily sum of solar radiation at the upper boundary of the atmosphere [cal cm^{-2} day^{-1}],
α – the albedo, α=0.20,
S – average actual insolation in a month [hours],
S_0 – astronomically possible insolation [hours],
σ – the Stefan-Boltzman constant [cal cm^{-2} day^{-1} K^{-1}],
T_A – monthly average air temperature [K],
e – monthly average water-vapour pressure [hPa],
Δ – pressure gradient of the saturated water-vapour at average air temperature [hPa K^{-1}],
e_w – saturated water-vapour pressure at a given temperature [hPa],
v – monthly average wind speed 10 m above ground [m s^{-1}].

The equation for the potential evapotranspiration according to Turc (1964):

$$E_T = 0{,}4\frac{t}{t+15}\left[G_0\left(0{,}209 + 0{,}565\frac{S}{S_0}\right) + 50\right]$$

where:
E_T – the monthly sum of the potential evapotranspiration according to Turc [mm month^{-1}],
t – monthly average air temperature [°C],
G_0 – daily sum of solar radiation at the upper boundary of the atmosphere [cal cm^{-2} day^{-1}],
S – average actual insolation in a month [hours],
S_0 – astronomically possible insolation [hours].

The presented equations according to Penman and Turc are empirical formulae in which the numerical coefficients are expressed in obsolete systems of units. Consequently, one cannot apply to them the solar radiation values expressed in the SI units.

The equation for the indicatory evaporation according to Bac (1970) is of the form:

$$E_o = 3 \cdot d\sqrt{v} + 0{,}344\,T$$

where:
E_o – the monthly sum of the indicatory evaporation according to Bac [mm month^{-1}],
d – monthly average water saturation deficit [hPa],
v – monthly average wind speed 10 m above ground [m s^{-1}],
T – monthly sum of total radiation [kWh m^{-2}].

The collected data were analysed with the Hess method (1965, 1966, 1968, 1969) of determining the relationships between altitude and the values of individual elements and climatic indicators, with a simultaneous evaluation of the quantitative connections between them. In addition, local climatic peculiarities were taken into account, by separately considering the basic types of the terrain (convex and concave forms). This is especially important due to the fact that the spatial variability of precipitation is much greater than that of evaporation. It also allows for the obtaining of more realistic spatial and dynamic distributions of climatic water balances for the Polish Carpathians. It was not possible, however, to present the influence of slope aspect on climatic conditions in the researched hypsometric profile, due to a lack of suitably located stations. The fact that the stations were localised along the 20°E meridian rendered it impossible to evaluate the impact of the geographical longitude (horizontal gradients) on the researched climatic indicators. Basic statistical parameters and linear regression and correlation analysis were used in this study.

In order to develop a method for computing the total evaporation from the meteorological data for the Polish Carpathians, independent verification of semi-annual sums of the potential evapotranspiration (according to Penman and Turc) and the indicatory evaporation (according to Bac) has been carried out by conducting comparisons with hydrological data. In hydrological computations, one may assume that, for a sufficiently long period of time and for averaged values, the differences between influx of precipitation (P) and runoff (H) define either the deficit of runoff (D) or the losses identified with total evaporation (for a multi-annual period, and while the retention state change approaches zero). Total evaporation is described then as equal to the deficit of runoff. This relationship is valid for the case of a one-year period taken from a long-term period, with the assumption that the individual elements of the water balance were estimated without error. In this study, an attempt has been made at applying this relationship for the summer half-year (May-October), after taking into account the large inertia of the precipitation-runoff system, a phenomenon well known in hydrology.

The comparison of the results has been conducted using the examples of the catchment areas of the Skawa river (up to the Wadowice water-gauge), the Raba river (up to the Proszówki water-gauge) and the Dunajec (up to the Nowy Targ – Kowaniec water-gauge), with average values of the raw water balance for the summer half-year (May-October) from the 1951-1970 period (Tab. 2). Such comparison seems to be the most meaningful, since total evaporation is that element of the water balance whose equation is considered with respect to the catchment area, and not with respect to the individual points of the area. Influences of the local conditions on such points are highly variable.

Consequently, the lines of equal potential evapotranspiration (according to Penman and Turc) and the equal indicatory evaporation lines (according to Bac) were drawn on sketch maps (1:300 000 map scale) for the Skawa, Raba and Dunajec catchment areas. They were drawn for the summer half-year (May-October), and separately for the periods between 1951-1960, and 1951-1970, using linear regression equations computed from the data originating from 25 meteorological stations. The regression equations described the dependence of the evaporation indices on altitude, taking into account both the convex and concave forms of the terrain in the studied

Tab. 2. Averages from the years between 1951-1960 and (1951-1970) of the summer half-year (May-October) values, of the elements of the raw water balance (P- standard precipitation, P` – real precipitation, H- runoff, D` – corrected deficit of runoff), and potential evapotranspiration according to Penman (E_p), Turc (E_T), indicatory evaporation according to Bac (E_o), index of total evaporation ($E`_o$), correction coefficient (K`), and climatic water balance ($P-E`_o$) in the catchment areas of the Raba, Skawa and Dunajec rivers.

Tab. 2. Zestawienie średnich z lat 1951-1960 i (1951-1970) półrocznych (V-X) wartości elementów surowego bilansu wodnego (P- opad standardowy, P` – opad rzeczywisty, H – odpływ, D` – poprawiony deficyt odpływu) oraz ewapotranspiracji potencjalnej wg Penmana (E_p), Turca (E_T), parowania wskaźnikowego wg Baca (E_o), wskaźnika parowania terenowego ($E`_o$), współczynnika korekcyjnego (K`) i klimatycznego bilansu wodnego ($P-E`_o$) w zlewni Raby, Skawy i Dunajca.

Catchment area *Zlewnia*	Raba	Skawa	Dunajec
water - gauge *wodowskaz*	Proszówki	Wadowice	Nowy Targ - Kowaniec
A_C (km^2)	1470	836	681
$h_{mean - średnia}$ (m)	423	536	836
wooded area - lesistość (%)	35.1	45.1	38.0
P (mm)	551.2 (575.6)	619.8 (645.6)	686.0 (704.1)
P` (mm)	632.8 (660.8)	698.5 (727.6)	773.1 (793.5)
H (mm)	165.0 (186.9)	191.1 (217.8)	371.9 (406.4)
P`-H=D` (mm)	467.8 (473.9)	507.4 (509.8)	401.2 (387.1)
E_P (mm)	496.5 (499.0)	484.6 (487.0)	452.0 (454.3)
E_P/D`=K`	1.06 (1.05)	0.96 (0.96)	1.13 (1.17)
E_T (mm)	496.6 (501.6)	476.5 (481.3)	420.9 (425.1)
E_T/D`=K`	1.06 (1.06)	0.94 (0.94)	1.05 (1.1)
E_0 (mm)	376.5 (378.4)	370.2 (372.0)	352.5 (354.3)
E_0/D`=K`	0.80 (0.80)	0.73 (0.73)	0.88 (0.92)
$E`_0$ (mm)	**436.6 (440.0)**	**423.4 (426.6)**	**386.7 (389.7)**
$E`_0$/D`=K`	**0.93 (0.93)**	**0.83 (0.84)**	**0.96 (1.01)**
$P-E`_0$ (mm)	114.6 (135.6)	196.4 (219.0)	299.7 (314.4)
$(P-E`_0)/H$ (mm)	0.694 (0.726)	1.028 (1.006)	0.806 (0.774)
precipitation deficit (mm)	**-50.4 (-51.3)**	**5.3 (1.2)**	**-72.2 (-92.0)**
niedomiar opadów %	**9.1 (8.9)**	**0.8 (0.2)**	**10.5 (13.1)**

(...) - data 1951-1970 (...) - dane z lat 1951-1970

hypsometric profile. Next, weighted averages of the potential evapotranspiration (according to Penman and Turc) and the indicatory evaporation (according to Bac) were determined for these catchment areas, using area planimetry (Tab. 2).

Significant differences have been detected in comparisons of runoff deficits, which is the function of precipitation and runoff, with the analysed indices of evaporation. The obtained values of the correction coefficients (K), which are the ratio E/D, range from 1.13 to 1.44 for the potential evapotranspiration according to Penman (E_p), from 1.11 to 1.34 for the potential evapotranspiration according to Turc (E_T), and from 0.86 to 1.12 for the indicatory evaporation (E_o) according to Bac (data from 1951-1960). One should consider whether the values of the evaporation indices are too high relative to the real evaporation, and whether water influx due to precipitation (as shown in Table 2) is real.

Numerous authors have pointed out that there exist differences between precipitation sums measured with a standard rain gauge and the real influx per unit area. Analyses of the type of the observed deviations suggests that their cause should be sought mainly in the methods with which precipitation is measured. In the case of modelling a given object (observation point, catchment area), the influx input values are much greater than those used before. Currently, the most useful in hydrological practice in mountainous areas are corrections of 13-15% for the summer half-year (May-October), as developed by Chomicz (1976).

The magnitude of precipitation in individual catchment areas (P`) was corrected using Chomicz's correction factors, taking into account the average altitude of those areas. Next, corrected deficits of runoff (D`) were computed. The values of the correction coefficients (K`=E/D`) obtained as a result of using the corrected values for precipitation, are in six cases out of nine (i.e. 67%) closer to unity than the corresponding values of the K coefficients (Tab. 2). As the computations showed, the values of the correction coefficients (K`=E/D`) obtained when using the real precipitation estimates are uni-directional. They most closely approach unity in the cases of the arithmetic average of the potential evapotranspiration (E_T) and the indicatory evaporation (E_o), and range from 0.83 to 0.96 (data from 1951-1960). The values of the correction coefficients (K`), shown in Table 2, developed from the data from the period between 1951-1970, do not differ much from the 1951-1960 averages and range from 0.84 to 1.01. Consequently, the value of evaporation adopted as the closest to the real one, was equal to the arithmetic average of the potential evapotranspiration according to Turc (E_T) and the indicatory evaporation according to Bac (E_o), i.e.:

$$\frac{E_T + E_o}{2} = E_o^{'} \quad \text{or} \quad E_o^{'} = k \cdot E_o$$

where:
k – the proportionality coefficient = $E`_o / E_o$.

The values of the total evaporation index ($E`_o$) obtained in this manner were taken as the basic reference values in further studies of the climatic water balance for the Polish Carpathians. The computation of the climatic water balances utilised standard precipitation values. This decision reflects a necessity until real precipitation measurements are collected at meteorological stations.

Verification of the summer half-yearly (May-October) sums of the climatic water balance (P-$E`_o$) using runoff indicators (H) demonstrated a slight „deficit" of precipitation in the balance (6.3-7.3%, on average), under the assumption, that the index of total evaporation reflects the actual deficits of runoff (Tab. 2). The observed „deficits" of precipitation may confirm the phenomenon of a substantial inertia in the precipitation-runoff system during the summer half-year, a well-known fact in hydrology. Moreover, the magnitudes of the precipitation „deficits" are in agreement with the results obtained by Rojek for the area of southern Poland (Rojek 1984) and by Pasela and Zawora (1984) obtained in the vicinity of Kraków. A lack of precipitation „deficit" in the Skawa catchment area (characterised by the highest percentage of the forested area, 45.1%), and the most pronounced „deficit" in the catchment areas of the Dunajec and Raba rivers (characterised by the lowest percentage of the forested area, 38.0% and 35.1%, respectively), may probably be explained by the phenomenon of interception, which leads to a reduced amount of water from precipitation wetting the surface of the soil.

It is also worth noting, that in the Carpathian catchment areas one may expect not only errors in the precipitation measurements, but also in the measurements of runoff (Dynowska 1991). Given the current state of knowledge about the conditions affecting river runoff and about the accuracy of the measurements, it is impossible to formulate final conclusions about the magnitude of the errors. Therefore, the index of total evaporation ($E`_o$) may be taken as being close to the magnitude of the actual loss of water from the unit area during the summer half-year (May-October) in the Polish Carpathians. Consequently, comparisons of the climatic water balance (P-$E`_o$) with the runoff during the summer half-year are justified.

5. Spatial and dynamic distribution of the index of total evaporation ($E`_o$) and the climatic water balance (P-$E`_o$)

From the linear regression equations, developed separately for both convex and concave land-forms, which describe the dependence of the analysed climatic indicators on altitude, it became possible to present the spatial distribution of the obtained results (Kowanetz 1998). The maps of the index of total evaporation and of the climatic water balance were drawn to the 1:300 000 scale for the summer half-year (May-October) and the consecutive months. The area covered three catchment areas: Skawa (up to the Wadowice water-gauge), Raba (up to the Proszówki water-gauge) and Dunajec (up to the Nowy Targ – Kowaniec water-gauge). The selected maps included with this study were reduced in size for technical reasons (Fig. 2-8).

The distribution of total evaporation in the studied area is determined by the parallel arrangement of the basic physico-geographical units. The values of the equal evaporation lines vary depending on the values of the factors influencing evaporation, i.e. total radiation, water-vapour capacity of the atmosphere, and air movement. The highest values of total evaporation during the entire summer half-year (May-October)

Fig. *2*. Average sums of the index of total evaporation ($E`_o$, mm) during the summer half-year (May-October) in the Polish Carpathians.

Ryc. *2*. Średnie sumy wskaźnika parowania terenowego ($E`_o$, mm) w półroczu letnim (V-X) w Karpatach Polskich.

Fig. 3. Average sums of the index of total evaporation (E`$_{o}$, mm) in July in the Polish Carpathians.

Ryc. 3. Średnie sumy wskaźnika parowania terenowego (E`$_{o}$, mm) w lipcu w Karpatach Polskich.

are concentrated in the regions of the lowest altitude, while the lowest values occur on the Tatra mountain summits. During the autumn, and especially in October, there is a weak decline in the values of the total evaporation index ($E`_o$) with increasing altitude (Fig. 2-4). Warming of the air in the valleys and basins especially in the spring and summer, and (associated with this phenomenon) convection and condensation of water vapour on hillsides, causes an increase in total evaporation ($E`_o$) in the concave forms of terrain during the months of the summer half-year. In October, there are relatively high sums of total evaporation ($E`_o$) in the high-mountain zone of the Carpathians, due to a higher frequency of anticyclonal situations. Such situations are characterised by a lesser cloud cover and greater influx of solar radiation. In the case of advection-free anticyclonal situations, they are also characterised by high deficits of air humidity during „sinking" and warming of the air (the, so-called, „sinking or free-foehns", Niedźwiedź 1981). Moreover, a slight decline in the sums of the total evaporation index in October on the Beskids and Tatra summits is presumably associated with the predominant air advection from the southern sector and with the impact of the classic foehn winds (Ustrnul 1991).

The spatial distribution of the average sums of the climatic water balance ($P-E`_o$) during the summer half-year (May-October) and its selected months is presented in the enclosed maps (Fig. 5-8). The difference between the maximum and minimum values of the index ($P- E`_o$) is over 700 mm during the summer half-year (May-October), and small precipitation deficits ($P-E`_o<0$) occur only in some sub-Carpathian basins (the Northern Podkarpacie). The equilibrium line for precipitation and total evaporation ($P=E`_o$) already runs in concave forms at an elevation of 210 m above sea level, and in convex forms of the terrain – at 250 m (Fig. 5). The highest precipitation excesses (over 700 mm) occur on the summits in the Beskid Żywiecki and the Tatra mountains. Larger parts of the Orawsko-Nowotarski Basin, the Orawsko-Jordanowski Foothills, and the Średni and Wyspowy Beskid constitute areas with precipitation excesses from 100 to 200 mm. In the vicinity of the Brama Sieniawska (the Orawsko-Jordanowski Foothills) there is precipitation surplus exceeding 200 mm, and on the summits of the Beskid Wyspowy – of 200 mm, the Beskid Mały 300 mm, and on the summits of the Gorce they equal 500 mm.

The equations of the climatic water balances for the summer half-year (May-October) reveal their uneven distribution among the individual months (Fig. 6-8). In the lower-elevation section of the altitude profile researched (up to an elevation of 800 m above sea level), the largest sums of the climatic water balance are mostly observed in July, due to maximum precipitation occurring during that month. At elevations above 800 m, the maximum climatic water balances occur in June, and coincide with the maximum precipitation at those elevations.

For May, the equilibrium line of precipitation and total evaporation ($P=E`_o$) runs in concave forms of the terrain at an elevation as high as 410 m above sea level, and in convex forms even higher, at 520 m (Fig. 6). The largest precipitation deficits in May (below –20 mm) occur over the whole area of the Northern Podkarpacie, since the „–20" isoline of the $P- E`_o$ index runs in concave forms of the terrain at the elevation of 220 m above sea level, and in convex forms at 330 m above sea level.

Fig. 4. Average sums of the index of total evaporation (E\`$_o$, mm) in October in the Polish Carpathians.

Ryc. 4. Średnie sumy wskaźnika parowania terenowego (E\`$_o$, mm) w październiku w Karpatach Polskich.

Fig. 5. Average sums of the climatic water balance (P-$E`_{o}$, mm) during the summer half-year (May-October) in the Polish Carpathians.

Ryc. 5. Średnie sumy klimatycznego bilansu wodnego (P-$E`_{o}$, mm) w półroczu letnim (V-X) w Karpatach Polskich.

Fig. 6. Average sums of the climatic water balance (P-$E^{`}_{o}$, mm) in May in the Polish Carpathians.

Ryc. 6. Średnie sumy klimatycznego bilansu wodnego (P-$E^{`}_{o}$, mm) w maju w Karpatach Polskich.

Fig. 7. Average sums of the climatic water balance (P-E`$_o$, mm) in June in the Polish Carpathians.

Ryc. 7. Średnie sumy klimatycznego bilansu wodnego (P-E`$_o$, mm) w czerwcu w Karpatach Polskich.

Fig. 8. Average sums of the climatic water balance (P-E`$_o$, mm) in September in the Polish Carpathians.

Ryc. 8. Średnie sumy klimatycznego bilansu wodnego (P-E`$_o$, mm) we wrześniu w Karpatach Polskich.

In the climatic conditions of the Polish Carpathians, June is the month of the highest precipitation excess in the high-mountain zone (Fig. 7). The values of the P-$E`_o$ index in June are 50-75 mm higher than in May, and range from below 25 mm in the Northern Podkarpacie up to over 200 mm on the Tatra summits, indicating precipitation excesses in the entire studied area.

In September, precipitation deficits are lower than in May. The line of equilibrium between precipitation and total evaporation ($P=E`_o$) runs in the concave forms of the terrain at an elevation of 395 m above sea level, and in convex forms at 410 m (Fig. 8). The largest precipitation deficits (below –10 mm) occur in the areas of the lowest elevation in the sub-Carpathian basins and in the Carpathian Foothills. In September, there are also small precipitation deficits (down to –5 mm) in the Orawsko-Nowotarski Basin and the Orawsko-Jordanowski Foothills. Small precipitation excesses ($P-E`_o>0$) are observed in the area of Brama Sieniawska.

6. Discussion of the results

The presented results of the study point to a significant regional differentiation and, therefore, to the need for characterising the moisture degree of the Polish Carpathians on the basis of the climatic water balances. It is difficult to compare the values of the total evaporation index and of the climatic water balances presented in this study with the results of other authors, since different methods and various indices of evaporation were used.

The method used in this study for determining the total evaporation, is based on independent verification of the value of evaporation computed from meteorological data (the indirect method), by comparing it with the hydrological data (deficit of runoff). Moreover, the application of linear regression and correlation methods enabled the development of maps (with map scale of 1:300 000) presenting spatial distribution of the total evaporation index ($E`_o$) and the climatic water balance ($P-E`_o$). It is therefore appropriate and sensible to discuss the obtained results in the light of the earlier studies.

There are very few publications in the Polish scientific literature concerning total evaporation and climatic water balance, in areas with a great diversity of terrain formations and with a large range of altitudes (both relative and absolute). Even those studies, however, are difficult to evaluate from a comparative perspective since they were based on different measurement periods. Although the research of Jaworski (1968) deals with the period between 1951-1960 and contains a map of the total evaporation computed with the water balance of catchment areas and standard precipitation method, it is based on a full-year period and covers the whole territory of Poland, however. The map drawn by Jaworski was included in the *Klimatyczny Atlas Polski* (Climatic Atlas of Poland, 1973). According to this map, the greatest differentiation of total evaporation occurs in the mountainous regions of southern Poland, where evaporation values range from 350 mm to 600 mm. The total evaporation value is given in the work by Gutry-Korycka (1978) and it is based on the maps of real precipitation and average runoffs within the catchment area, for the period between

1931-1960. The spatial distribution of total evaporation obtained by Gutry-Korycka for the full-year period is similar in its general characteristics to that presented by Jaworski. The mountainous zone is characterised by the greatest differentiation between the maximum and minimum values of evaporation (from 300 to 800 mm). It would, however, be inappropriate to compare those maps with the distribution of the total evaporation index ($E`_o$) obtained in this study, because different time periods were used.

According to Cetnarowicz (1971), total evaporation during the summer half-year (May-October) computed with the Konstantinow method ranges from 325 mm in the high-mountain zone of the Tatras to over 400 mm in the area of the Sandomierska Basin (data from 1951-1960). The values of total evaporation presented there are approximately 20% lower in the case of the Carpathian Foothills, and higher in the high-mountain zone, compared to the values obtained in this study. The maps of total evaporation contained in the *Hydrologiczny Atlas Polski* (Hydrological Atlas of Poland, Szkutnicka 1986) are also based on the evaporation values computed with the Konstantinow method (data from the period between 1951-1970). According to Szkutnicka, the sums of total evaporation for the summer half-year (May-October) in the studied area ranged from less than 360 mm (at higher elevations in the Carpathians) to more than 420 mm in the foothills. However, compared to the values of the total evaporation index computed in the current study, the quoted sums of total evaporation during the summer half-year are approximately 20% lower at the lower elevations of the researched profile, and approximately 30% higher in the high-mountain section. The latest work on this topic (Danielak and Lenart 1989) contains maps of the potential evaporation and total evaporation (Budyko's complex method), for quarterly periods (seasons) and the entire year (averages from the period between 1951-1970), but it does not cover mountainous regions. Similarly, Rojek and Wiercioch, in one of the latest studies (1995), developed a spatial distribution of total evaporation of the soil without vegetation, for lowland Poland. These authors obtained values of total evaporation during the summer half-year (April-September) in the Carpathian Foothills, that were much lower (about 330 mm).

The results of research to date indicate that there is substantial variation in the values of the potential evaporation in the area of the Polish Carpathians. It is worth stressing that the studied area has also been neglected or treated only cursorily in studies of the spatial distribution of potential evaporation. When comparing the results of Schmuck (1953) with the results obtained in this study, one may notice that the value of evaporation from the open water surface (E_w) is slightly higher in the high-mountain zone of the Carpathians during the summer half-year (May-October) than the value of total evaporation. It ranges from 300 mm to the much higher value of 600 mm in the Carpathian Foothills. Schmuck also presented a map of the half-year values of the ($P-E_w$) index, which range in the studied area from –200 mm in the Northern Podkarpacie up to over 500 mm in the Tatra mountains. The values of precipitation deficit according to Schmuck are much higher, and those of excesses – much lower, than the values obtained in this study.

The maps of evaporation from an open water surface (E_w), included in the *Hydrologiczny Atlas Polski* (Hydrological Atlas of Poland, Jurak 1986), were computed by the turbulence diffusion method and were based on the data from the period between 1951-1970. Average semi-annual (May-October) sums of evaporation from an open water surface range from approximately 400 mm in the high-mountain zone of the Carpathians to over 420 mm in the foothills. They are lower in the lower part of the researched profile, and higher in the high-mountain zone than the values of the total evaporation index obtained in this study.

Based on the meteorological data for the period between 1951-1970, Bac developed maps of the lines of equal indicatory evaporation (E_o), computed from his own formula, and of the lines of equal climatic water balance ($P\text{-}E_o$) for Poland – excluding the mountain region (Bac 1976, Bac and Rojek 1979, Bac et al. 1982). Values of indicatory evaporation for the half-year (April-September) in the Carpathian Foothills presented by Bac range from 400 to 420 mm and are approximately 15-20% lower than the value of the total evaporation index ($E`_o$). Similarly, Bac's values of climatic water balances differ from those obtained in this study, since they range from –50 to 0 mm in the Northern Podkarpacie to 200 mm in the foothills. The results of the present study indicate that they range from below 0 mm to over 100 mm. It is worth highlighting that spatial distribution maps of indicatory evaporation (E_o) in the lowland Poland area, included in the subsequent publications (Rojek 1987, Rojek and Wiercioch 1994, Bac et al. 1998) do not differ greatly and present similar values of indicatory evaporation sums for the Northern Podkarpacie. The problem of the spatial distribution of climatic water balance sums (P-E) in Poland (without the mountain region) was also addressed by Rojek, who developed maps of semi-annual (April-September) sums $P\text{-}E_o$ for the periods between 1951-1980 (Rojek 1987) and 1951-1990 (Rojek 1994, Bac et al. 1998). Maps of the climatic water balance for the half-year (April-September) from consecutive long-term periods, do not differ greatly and present sums similar to the average values for the years between 1951-1970 in the Northern Podkarpacie.

According to Krzanowski (1976), values of the maximum possible total evaporation computed for an average hydrological year (between 1951-1960) in the Carpathian area of the Vistula river basin, range from 390 mm in the upper alpine zone to 780 mm in the Mielec-Dębica-Tarnów triangle. Sums of the maximum possible total evaporation in the summer half-year (May-October) are much higher than the values obtained in this study. Krzanowski also documented a distinct decline with elevation in the annual average sums of the maximum possible total evaporation. Such a decline results from his adoption of the Thornthwaite's formula in which evaporation is a function of air temperature.

According to the data of Olechnowicz-Bobrowska (1978), in the Polish Carpathians and the foothills all four, as described in Poland, zones of potential evaporation are present (determined by the Van Bavel method, with the data from 1956-1965). Between April and October, it varies from 500-550 mm in the Carpathians, to 550-650 mm in the Carpathian Foothills, to 650-750 mm in the Krakowsko-Częstochowska Upland, and up to 750-850 mm in the Sandomierska Basin and in the

Roztocze. The values of the potential evaporation presented by Olechnowicz-Bobrowska (1978) are much higher than the values of the total evaporation index computed in this study.

Olechnowicz-Bobrowska (1978) also developed maps of the climatic water balance for the territory of Poland during the vegetation period (April-October) and during each of its months. The values of the index, being the difference between precipitation and potential evaporation, determined by the Van Bavel method during the vegetation period in the studied area, range from less than –200 mm in the Northern Podkarpacie, to over 300 mm in the Tatra mountains. The largest excesses of precipitation, reaching in the Tatras over 100 mm in June and over 60 mm in July, occur during the months when water is especially critical for plant growth and development. The most pronounced precipitation deficits in the Carpathians, according to Olechnowicz-Bobrowska (1978), are as large as –40 mm in April (from –40 to 20 mm in May) and –20 mm in September, and occur only in the lowest parts of the Carpathians. The values of the average climatic water balance during the summer half-year (May-October), as reported in this study, are much higher and range from less than 0 mm in the western part of the Sandomierska Basin, to over 700 mm in the high-mountain zone of the Carpathians. The recorded precipitation deficits are also lower and in the Carpathian foothills they are below –20 mm in May and –10 mm in September. There also occur pronounced precipitation excesses in the Tatras, exceeding 200 mm in June and 150 mm in July. One should also emphasise that the largest precipitation deficits obtained in this study occur in May and coincide with the beginning of the germination of spring crop cereals, and particularly with the critical moment of their coming to ear – which begins in the foothill basins in the third or fourth week of the month (Obrębska-Starklowa 1977).

Olechnowicz-Bobrowska (1978) has described as highly significant, the relationship between elevation above sea level and the P-E index. The defined relationship indicates that the line of equilibrium between precipitation and potential evaporation (P=E) runs at the elevation of about 540 m above sea level, i.e. much higher than that calculated in the present study (210 m in the concave forms and 250 m in the convex forms). As Olechnowicz-Bobrowska (1978, p. 96) concludes, it is justified „to continue further research on this topic in order to develop a more accurate relationship and, after the network of mountain stations has been expanded, to determine more precisely the elevation at which P=E".

Comparisons of the results obtained by various authors in the Polish Carpathians and the foothills lead one to conclude that the application of empirical formulae yields lower estimates of total evaporation for the low-elevation areas, and yields higher estimates, than those obtained in the present study, in the summit zone of the Beskidy and Tatra mountains. Adopting markedly higher values of potential evaporation will result in much higher estimates of precipitation deficits and lower estimates of precipitation excesses. Furthermore, using such estimates as reference points for computing climatic water balances does not yield the correct assessment of the moisture degree of the researched area.

7. Conclusions

The results obtained allow one to provide, for a complicated and methodologically challenging area of the Polish Carpathians, a detailed presentation of the spatial and temporal distribution of climatic water balance and of its basic component, namely total evaporation. The developed method may be used for determining and predicting the values of total evaporation (actual evapotranspiration) in the mountain regions, which is of particular significance in agriculture for assessing precipitation deficits and excesses. One should emphasise that the climatic water balance may serve as the basis for the assessment of irrigation needs only in connection with soil water resources, i.e. of water available to plants.

The presented method may be used in studies in the field of the mathematical modelling of runoff processes and in estimating water resources of small uncontrolled catchment areas (as part of the design and study work). Numerical values of the climatic water balances will be modified with the introduction of the real values of water input from the atmosphere. Verification of the proposed method is possible with the use of experimental catchment areas which guarantee detailed measurements of all the components of the water balance.

References

Atlas Hydrologiczny Polski (Hydrological Atlas of Poland), 1986, IMGW, Warszawa

Atlas Klimatyczny Polski (Climatic Atlas of Poland), 1973, IMGW, PPWK, Warszawa

Bac S., 1970, *Badania nad współzależnością parowania z wolnej powierzchni wodnej, parowania terenowego i ewapotranspiracji potencjalnej*, Prace i Studia Komit. Gosp. Wodn. i Sur., PAN, t. X, 287-366.

Bac S., 1974, *Klimatyczny bilans wodny Południowo-Zachodniej Polski*, Materiały Sesji Naukowej „Wykorzystanie i ochrona środowiska ziem Południowo-Zachodniej Polski", Komisja Nauk o Ziemi, PAN, Wrocław

Bac S., 1976, *Kryteria klimatyczne lokalizacji nawodnień w Polsce*, Zesz. Probl. Post. Nauk Roln., z. 181, 617-636.

Bac S., Rojek M., 1979, *Meteorologia i klimatologia*, PWN, Warszawa, 1-248.

Bac S., Karpińska Z., Koźmiński C., Michalska B., Rojek M., Rojek S., 1982, *Agroklimatyczne podstawy melioracji wodnych w Polsce*, PWRiL, Warszawa, 1-313.

Bac S., Koźmiński C., Rojek M., 1998, *Agrometeorologia*, PWN, Warszawa, 1-275.

Cetnarowicz M., 1971, *Parowanie terenowe w Polsce w oparciu o analizę składników bilansu wodnego i sieciowe obserwacje elementów klimatu w dziesięcioleciu 1951-1960*, Prace PIHM, z. 104, 3-39.

Chomicz K., 1976, *Opady rzeczywiste w Polsce (1931-1960)*, Przegl. Geof. R. XXI (XXIX), z. 1, 19-25.

Czeppe Z., German K., 1979, *Regiony fizycznogeograficzne*, [w:] Atlas miejskiego województwa krakowskiego, PAN, Kraków

Czeppe Z., German K., 1988, *Regiony fizycznogeograficzne*, [w:] Atlas miejskiego województwa tarnowskiego, PAN, Kraków

Danielak D., Lenart W., 1989, *Wyznaczenie parowania terenowego w Polsce metodą kompleksową*, Rocz. AR, Poznań., t.CCI, Melior., 8, 41-51.

Dynowska I., 1991, *Bilans wodny*, [w:] Dorzecze górnej Wisły, cz. I, (pod red. I.Dynowskiej i M.Maciejewskiego), PWN, Warszawa-Kraków, 223-227.

Gutry-Korycka M., 1978, *Parowanie terenowe w Polsce (1931-1960)*, Przegl. Geof., R. XXIII (XXXI), z. 4, 295-299.

Hess M., 1965, *Piętra klimatyczne w polskich Karpatach Zachodnich*, Zeszyty Naukowe UJ, Prace Geogr., z. 11, 1-258.

Hess M., 1966, *O mezoklimacie wypukłych i wklęsłych form terenowych w Polsce Południowej*, Przegl. Geof., R. XI (XIX), z. 1, 23-35.

Hess M., 1968, *Metoda określania ilościowego zróżnicowania mezoklimatycznego w terenach górskich*, Zeszyty Naukowe UJ, Prace Geogr., z. 18, 7-26.

Hess M., 1969, *Główne problemy klimatologiczne Karpat*, Zeszyty Naukowe UJ, Prace Geogr., z. 23, 7-47.

Jaworski J., 1968, *Zróżnicowanie przestrzenne średniego rocznego parowania terenowego w Polsce*, Prace PIHM, z. 95, 15-28.

Jurak D., 1986, *Parowanie z powierzchni wody*, [w:] Atlas Hydrologiczny Polski, cz. II, (pod red. J.Stachý), IMGW, Warszawa, 181-187.

Kondracki J., 1994, *Geografia Polski. Mezoregiony fizyczno-geograficzne*, PWN, Warszawa, 1-287.

Kowanetz L., 1998, *Klimatyczny bilans wodny w dorzeczu górnej Wisły*, Praca doktorska wykonana w Zakładzie Klimatologii Instytutu Geografii UJ, Kraków, maszynopis, 1-196.

Krzanowski S., 1976, *Nowa formuła do obliczania średnich rocznych odpływów jednostkowych ze zlewni niekontrolowanych na obszarze karpackiego dorzecza Wisły*, Zesz. Nauk. Politechniki Krakowskiej, nr 3, Budownictwo Wodne i Inżynieria Sanitarna, z. 24, 93-119.

Niedźwiedź T., 1981, *Sytuacje synoptyczne i ich wpływ na zróżnicowanie przestrzenne wybranych elementów klimatu w dorzeczu górnej Wisły*, Rozprawy Habilitacyjne UJ, nr 58, 1-165.

Obrębska-Starklowa B., 1977, *Typologia i regionalizacja fenologiczno-klimatyczna dorzecza górnej Wisły*, Rozprawy Habilitacyjne UJ, nr 11, 1-235.

Olechnowicz-Bobrowska B., 1978, *Parowanie potencjalne w okresie wegetacyjnym w Polsce*, Zeszyty Naukowe AR w Krakowie, Rozprawy Habilitacyjne, nr 67, 1-173.

Olecki Z., 1989, *Bilans promieniowania słonecznego w dorzeczu górnej Wisły*, Rozprawy Habilitacyjne UJ, nr 157, 1-126.

Pasela E., Zawora T., 1984, *Kształtowanie się opadów atmosferycznych na poziomie 0 m i 1 m nad powierzchnią gruntu w okresie wegetacji*, Zesz. Probl. Post. Nauk Roln., z. 288, 53-63.

Podogrocki J., 1978, *Spatial distribution of global solar radiation in Poland*, Publ. Inst. Geophys. Pol. Acad. Sc., D-5 (120), 17-30.

Rojek M., 1984, *Ocena rzeczywistego przychodu opadów do powierzchni zlewni na podstawie klimatycznych bilansów wodnych i odpływów*, Zesz. Probl. Post. Nauk Roln., z. 288, 103-113.

Rojek M., 1987, *Rozkład czasowy i przestrzenny klimatycznych i rolniczo-klimatycznych bilansów wodnych na terenie Polski*, Zeszyty Naukowe AR Wrocław, Rozprawy nr 62, 1-67.

Rojek M., 1994, *Rozkład przestrzenny klimatycznych bilansów wodnych na terenie Polski w okresie 1951-1990*, Zeszyty Naukowe AR Wrocław, Inż. Środ. VI, z. 243, 9-21.

Rojek M., Wiercioch T., 1994, *Rozkład przestrzenny parowania wskaźnikowego na terenie Polski w okresie 1951-1990*, Zeszyty Naukowe AR Wrocław, Inż. Środ. VI, z. 243, 23-35.

Rojek M., Wiercioch T., 1995, *Zmienność czasowa i przestrzenna parowania wskaźnikowego, ewapotranspiracji aktualnej i niedoborów opadowych w Polsce nizinnej w okresie 1951-1990*, Zeszyty Naukowe AR we Wrocławiu, nr 238, Monografie VI, 1-51.

Sarnacka S., Brzeska J., Świerczyńska H., 1983, *Wybrane metody wyznaczania ewapotranspiracji potencjalnej*, Mat. Bad. Ser. Gosp. Wodn. i Ochr. Wód, IMGW, 1-35.

Schmuck A., 1952, *Suchość powietrza a stan wód we Wrocławiu*, Prace WTN, ser. B, nr 58, 1-38.

Schmuck A., 1953, *Parowanie z wolnej powierzchni wodnej w Polsce*, Spraw. WTN, t. 8, Dodatek 1, 1-20.

Stachý J., Biernat B., Dobrzyńska J., 1979, *Odpływ rzek polskich w latach 1951-1970*, Mat. Bad. IMGW, Ser. Spec., nr 6, 3-71.

Susze na obszarze Polski w latach 1951-1990, 1995, Mat. Bad. IMGW, ser. Gosp. Wod. i Ochr. Wód, 16, 1-140.

Synteza surowego bilansu wodnego Polski w latach 1951-1965 (The synthesis of the raw water balance of Poland in the years 1951-1965), 1971, Mat. PIHM, Warszawa

Szkutnicka J., 1986, *Parowanie terenowe*, [w:] Atlas Hydrologiczny Polski, cz. II, (pod red. J.Stachý), IMGW, Warszawa, 177-180.

Tomlain J., 1993, *Distribution of evapotranspiration on the territory of Slovakia*, Proc. of Symp. on Prec. and Evap., Bratislava, 20-24 Sept. 1993, vol. 3, 181-184.

Turc L., 1964, *Evapotranspiration potentielle mensuelle et décadaire. Son evaluation en fonction de donneés météorologiques*, Polsko-Francuskie Sympozjum Gospodarki Wodnej, b. IGW, WKiŁ, Warszawa

Ustrnul Z., 1991, *Wiatry fenowe w Karpatach Polskich*, maszynopis pracy doktorskiej w Zakładzie Meteorologii Regionalnej IMGW, Oddział w Krakowie, 1-170.

O metodzie wyznaczania klimatycznego bilansu wodnego w obszarach górskich na przykładzie Karpat Polskich

Streszczenie

Podstawę klimatycznej oceny zasobów wodnych obszaru powinien stanowić wskaźnik obejmujący rzeczywiste opady atmosferyczne i parowanie tj. klimatyczny bilans wodny. W artykule podjęto próbę wypracowania na podstawie (łatwo dostępnych) danych meteorologicznych i sprawdzenia w warunkach przyrodniczych Karpat Polskich, prostej i łatwej prawdopodobnie dającej wiarygodne wyniki, metody określania parowania terenowego – podstawowego elementu klimatycznego bilansu wodnego.

Opracowanie zostało oparte na danych obserwacyjnych z trzech zlewni: Skawy (po wodowskaz Wadowice), Raby (po wodowskaz Proszówki) i Dunajca (po wodowskaz Nowy Targ – Kowaniec) położonych w zachodniej części Karpat Polskich (ryc. 1). Posłużono się w pracy wynikami pomiarów z 25 stacji meteorologicznych zlokalizowanych mniej więcej wzdłuż południka 20°E na wysokościach od 200 m do 2000 m n.p.m. z lat 1951-1960, dla półrocza letniego (V-X). Ponadto wykorzystano wyniki pomiarów meteorologicznych z okresu dwudziestoletniego dla wybranych stacji (tab. 1). Posłużenie się w pracy często stosowanymi w praktyce światowej, jak i w Polsce formułami empirycznymi Penmana - modyfikacja francuska (E_p), Turca (E_T) i Baca (E_o) stworzyło możliwość sprawdzenia celowości ich stosowania w obszarach górskich.

Zastosowana w niniejszej pracy metoda wyznaczania parowania terenowego opiera się na niezależnej weryfikacji wartości parowania obliczonych na podstawie danych meteorologicznych (metoda pośrednia), przez porównanie z danymi hydrologicznymi – deficytem odpływu (tab. 2). W wyniku przeprowadzonej weryfikacji przyjęto wielkość parowania jako najbliższą rzeczywistej równą średniej arytmetycznej ewapotranspiracji potencjalnej według Turca (E_T) i parowania wskaźnikowego według Baca (E_o) czyli:

$$\frac{E_T + E_o}{2} = E_o^{'} \quad \text{lub} \quad E_o^{'} = k \cdot E_o$$

gdzie:
k – współczynnik proporcjonalności = $E`_o / E_o$.

Uzyskane w ten sposób wartości wskaźnika parowania terenowego ($E`_o$) posłużyły jako podstawowe wielkości odniesienia dla dalszych opracowań klimatycznego bilansu wodnego ($P-E`_o$) w Karpatach Polskich. W obliczeniach klimatycznych bilansów wodnych wykorzystano wartości standardowych opadów atmosferycznych (P), gdyż istnieje taka konieczność do czasu wprowadzenia na stacjach meteorologicznych pomiarów opadów rzeczywistych.

Równie ważnym celem pracy było przedstawienie przestrzenne uzyskanych wyników. Cel ten został zrealizowany przez zastosowanie prezentacji kartograficznej

w postaci map sum półrocznych i miesięcznych wskaźnika parowania terenowego i klimatycznego bilansu wodnego w skali 1:300000 dla zachodniej części Karpat Polskich (ryc. 2-8).

Opracowana metoda może służyć do wyznaczania i prognozowania wielkości parowania terenowego (ewapotranspiracji aktualnej) w obszarach górskich, co ma szczególne znaczenie dla rolnictwa przy ocenie niedoborów i nadmiarów opadów. Można ją będzie wykorzystać w pracach z dziedziny matematycznego modelowania procesu odpływu oraz przy szacowaniu zasobów wodnych małych zlewni niekontrolowanych w ramach prac projektowych i studialnych. Weryfikacja proponowanej metody jest możliwa na materiałach zlewni eksperymentalnej, gwarantującej dokładne pomiary wszystkich składowych bilansu wodnego.

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