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FACTORS AFFECTING NUTRIENT BUDGET IN LAKES OF THE R. JORKA WATERSHED (MASURIAN LAKELAND, POLAND)

II. HYDROLOGICAL BUDGET OF LAKES IN 1978 AND 1979*

ABSTRACT: A description is presented of the water cycle in four lakes of the r. Jorka watershed: Majcz Wielki, Inulec, Głębokie and Jorzec. Particular attention is given to seasonal variation of water cycle components, such as: inflow to lakes (including inflow by the r. Jorka, inflow by secondary streams and inflow from the immediate lake basin), river outflow from the lakes, magnitude of underground feeding of the lakes and changes in the volume of water retained in lake hollows. A summary of detailed water budgets of the lakes made it possible to assess the water exchange rate during the year and to follow its seasonal variations.

KEY WORDS: Lakes, water budget, precipitation, surface run-off, water exchange.

Contents

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1. INTRODUCTION

The aim of the study is to exactly identify and analyse the basic components of the water cycle in four lakes constituting the main hydrographic element of the r. Jorka watershed. The four lakes in question are: L. Majcz Wielki, L. Inulec, Głębokie L. and L. Jorzec (Fig. 1). Attention was in particular given to possibilities of water from various

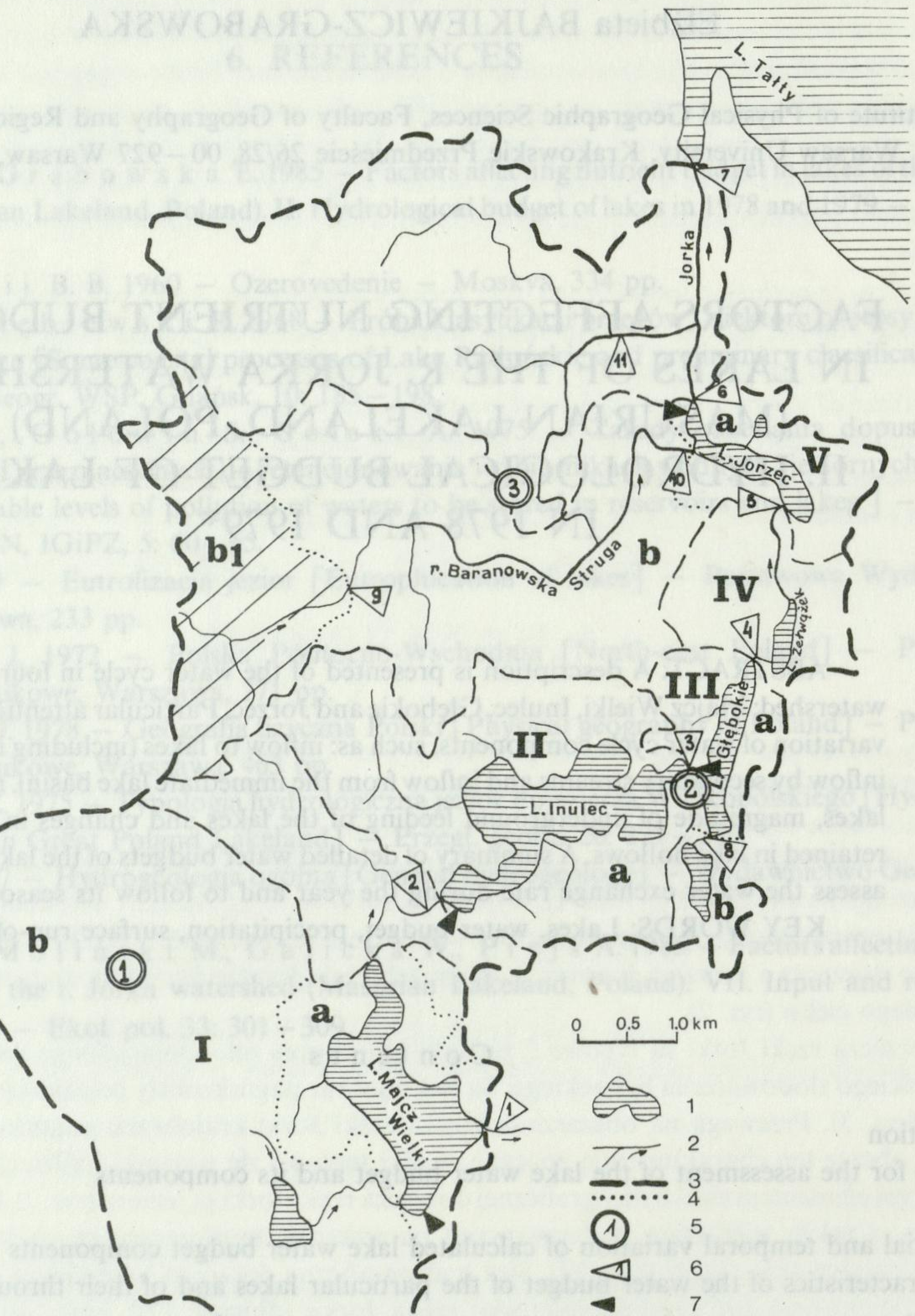

Fig. 1. Measurement-observation network in river Jorka watershed against the hydrographic division of the area

I – V – number of partial watershed, a – immediate watershed of the lake, b – watershed of a secondary tributary, b_1 – upper part of river Baranowska Struga watershed, 1 – lake, 2 – streams, 3 – water-partings of lake basins, 4 – water-partings of selected watersheds, 5 – precipitation station, 6 – hydrometric profile, 7 – water-gauge station. Description of the hydrographic division in the paper by Bajkiewicz-Grabowska (1985) sources being retained in the lakes. A physical-geographic description of the watershed under study (its climatic, geomorphological, hydrographic features), as well as a detailed morphometric description of the lakes studied can be found in the paper Bajkiewicz-Grabowska (1985).

2. METHODS FOR THE ASSESSMENT OF THE LAKE WATER BUDGET AND ITS COMPONENTS

Figure 2 presents the water cycle in a lake. The input consists of: precipitation on the lake surface (*Pj*), river inflow (*Hdrz*), i.e., inflow via the main watercourses, surface inflow from the immediate basin of the lake (*Hdp*) and two components of the underground inflow: subsurface inflow (*Hdg*) – input from the upper water-bearing horizon, i.e., the horizon that is potamic for the surface streams, and the groundwater inflow (*Hdpd*) – inflow from deeper water-bearing horizons that are apotamic for the surface streams, but are drained by the lake. The latter component of underground inflow may play an important role in deeper, mainly channel-type lakes. Underground feeding of lakes probably takes place in the littoral zone and on the slope of the lake hollow.

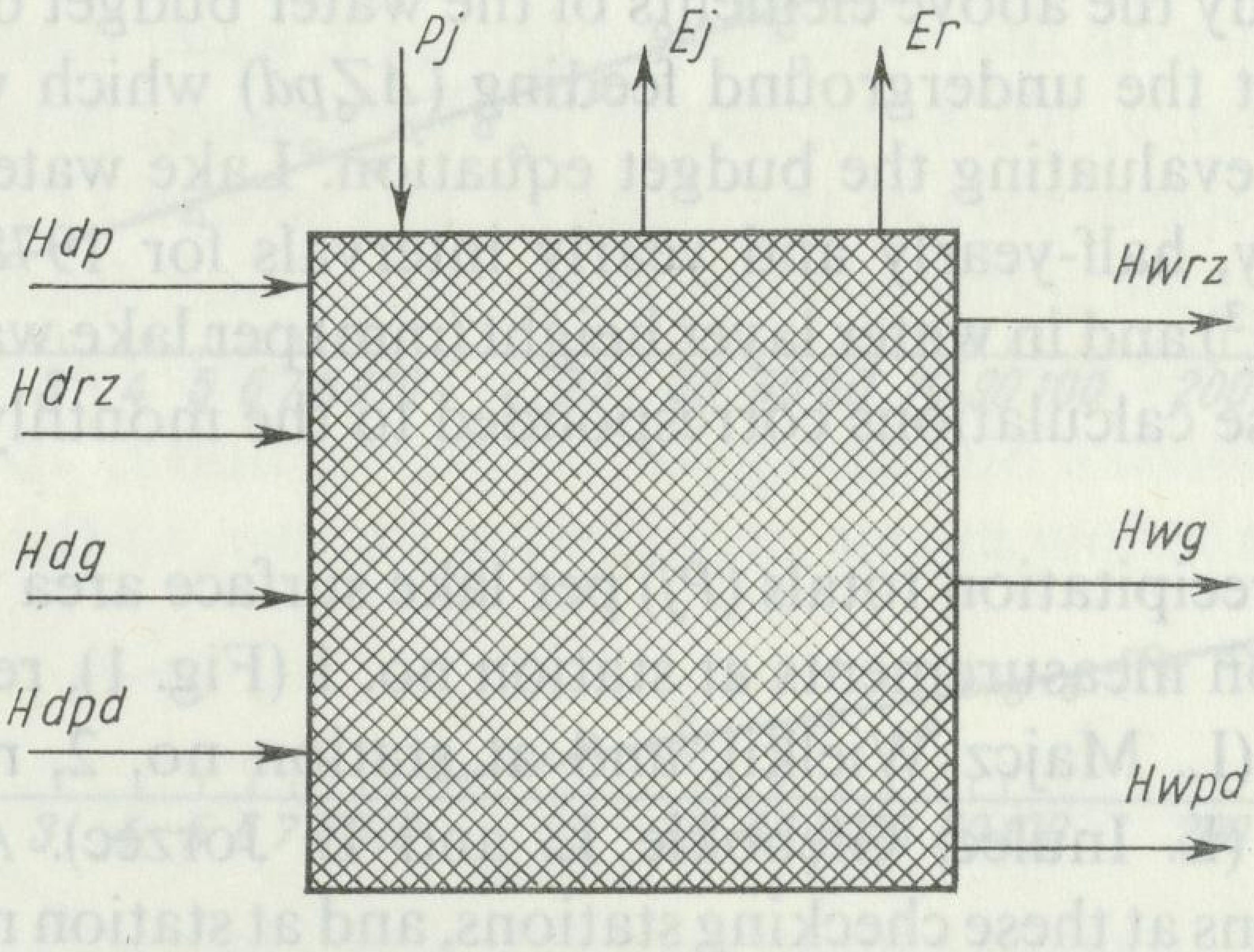

Fig. 2. A diagram showing the water cycle in lakes
Pj – precipitation on the lake surface, *Ej* – evaporation from the lake surface, *Er* – evaporation from the macrophyte belt, *Hdp* – surface inflow from the immediate watershed, *Hdrz* – river inflow, *Hdg* – subsurface inflow, *Hdpd* – groundwater inflow, *Hwrz* – river outflow, *Hwg* – subsurface outflow, *Hwpd* – underground outflow

On the expenditure side are the following budget components: evaporation from free water surface (*Ej*), evaporation from the emergent macrophyte belt (*Er*) – extremely important in the case of heavily overgrown lakes, surface outflow by streams (*Hwrz*) and groundwater outflow consisting of subsurface outflow (*Hwg*) and underground outflow (*Hwpd*). Water input and expenditure in a lake are manifested by water-surface level variations indicative of changes in the lake retention (*ΔRj*).

According to Mikulski and Bojanowicz (1966), the water budget of a lake can be presented in the form of an equation illustrating the vertical and horizontal water exchange in a lake:

$$(Pj - Ej) + (\Sigma Hd - \Sigma Hw) = \Delta Rj$$

where: Pj and Ej – as explained above, ΣHd – total inflow to the lake, ΣHw – total outflow from the lake, ΔRj – difference in lake retention at the beginning and at the end of the budget period. As it is difficult to independently calculate the components of underground inflow and outflow, i.e., Hdg, $Hdpd$, Hwg and $Hwpd$, in the present study they have been treated jointly as underground feeding ΔZpd. A plus sign against this component indicates that the lake accumulates water from underground sources, and a minus sign indicates that the lake returns water to the basin by underground outlet. Underground supply so understood is the resultant of underground inflow and outflow.

A detailed equation of the water budget of a lake, modified according to the above considerations, has the following format:

$$(Pj - Ej) + (Hdrz + Hdp - Hwrz) + \Delta Zpd = \Delta Rj$$

In the present study the above elements of the water budget of lakes were assessed independently, except the underground feeding (ΔZpd) which was determined as a budget difference by evaluating the budget equation. Lake water budgets have been expressed at monthly, half-yearly and yearly intervals for 1978 and 1979 in water volume units (mlln. m^3) and in water layer height (mm) per lake water surface area. The lake area used in these calculations corresponded to the monthly mean water surface state (Fig. 11).

Monthly mean precipitation totals (Pj) per lake surface area were calculated from circadian precipitation measurements at station no. 1 (Fig. 1), representing the forest precipitation region (L. Majcz Wielki), and at station no. 2, representing the lake precipitation region (L. Inulec, Głębokie L. and L. Jorzec). A detailed course of precipitation variations at these checking stations, and at station no. 3, representing the precipitation region of the agricultural part of the watershed, and a comparison with the recordings at the Mikołajskie L. weather station can be found in the paper Bajkiewicz-Grabowska (1985).

Evaporation from the lake surface (Ej) is the total of evaporation from the free water surface and from the surface occupied by emergent vegetation. However, it is difficult to assess these two components independently without special studies. As emergent vegetation covers a considerable proportion of lake surface area (from about 7% in Głębokie L. to 15% in L. Inulec – acc. to Bajkiewicz-Grabowska 1985), it has been assumed that the magnitude of evaporation from the lake water surface approaches the expected evaporation total, as calculated according to Dawidow's (Bac 1974) formula:

$$Ep = 15d^{0.8}(1 + 0.125w_{1000})$$

where: Ep – monthly mean evaporation total, d – monthly mean air-humidity deficit, determined from measurements with an August psychrometer as recorded at the Mikołajskie L. weather station, w_{1000} – monthly average wind velocity 10 m above ground, recorded at the same weather station. Air humidity and data on the variation of wind velocity and directions can be found in the paper Bajkiewicz-Grabowska (1985).

The monthly mean river inflow to a lake (*Hdrz*) was determined on the basis of the monthly mean water state in the lake and the discharge rate, measured once a month, of the main watercourses supplying the lake (Fig. 1). Data from four lake stations (L. Majcz Wielki, L. Inulec, Głębokie L. and L. Jorzec) were available, as well as water discharge measurements from eleven measurement sections mainly in the Jorka r. and Baranowska Struga r. (Fig. 1). Water states in the lakes were measured every day, from 30 October 1977 to 6 November 1979, and the discharge rate was measured once a month, from 1 November 1977 to 1 November 1979. Water discharge was measured indirectly by using an Ott type river-gauge. Lake water states were read from lake gauges in the form of detached staff gauges with one-sided 2 cm-calibration, levelled down to the geodetic network.

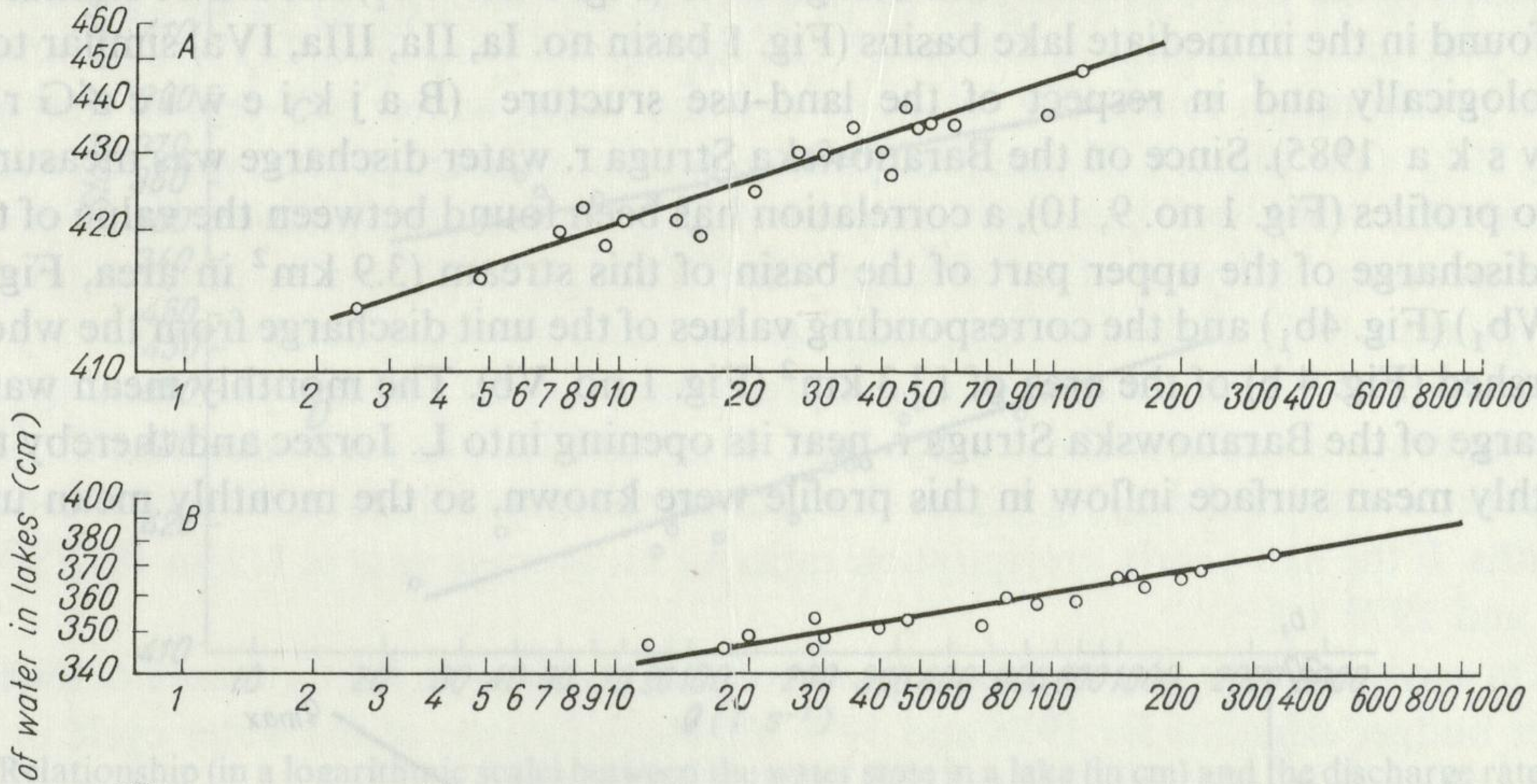

Fig. 3. Relationship (in a logarithmic scale) between the water state in a lake (in cm) and the discharge rate of a stream above its opening into a lake (in $l \cdot s^{-1}$)

1 – measurements of the discharge rate of the river Jorka, 2 – measurements of the discharge rate of the river Baranowska Struga, A – L. Inulec, B – Głębokie L., C – L. Jorzec

As the rate of discharge of tributaries to the lakes was often measured under disturbed conditions (overgrowth with vegetation) and at different dates, the relationship between the measured values of the discharge rate of permanent tributaries and the lake water states corresponding to the measurement dates has been represented graphically (Fig. 3). The relationship has been determined for three lakes, the tributaries of which are permanent watercourses (Fig. 1), that is, L. Inulec, Głębokie L. (permanent tributary r. Jorka) and L. Jorzec (two permanent tributaries: r. Jorka and r. Baranowska Struga). As the monthly mean lake water state was known, the corresponding water discharge could be read from the relationship, and then the monthly inflow to the lakes could be determined from the water discharge found.

Inflow from the immediate lake basin (*Hdp*) was calculated on the basis of the unit discharge in the basin. Most of the watercourses carrying water to the lakes are seasonal watercourses, which makes their checking difficult. These watercourses only function in the season of high water table states. They carry small amounts of water – the maximum water discharge found does not exceed 10 l·s^{-1} (Bajkiewicz-Grabowska 1985). Inflow to the lakes from their immediate basin was determined by the analogy method. It was assumed that the unit discharge in the upper part of the basin of the Baranowska Struga river (Fig. 1 no. Vb$_1$) should be similar to that found in the immediate lake basins (Fig. 1 basin no. Ia, IIa, IIIa, IVa) similar to it hydrologically and in respect of the land-use sructure (Bajkiewicz-Grabowska 1985). Since on the Baranowska Struga r. water discharge was measured in two profiles (Fig. 1 no. 9, 10), a correlation has been found between the value of the unit discharge of the upper part of the basin of this stream (3.9 km^2 in area, Fig. 1 no. IVb$_1$) (Fig. 4b$_1$) and the corresponding values of the unit discharge from the whole watershed (Fig. 4 b) of the area of 13.3 km^2 (Fig. 1 no. Vb). The monthly mean water discharge of the Baranowska Struga r. near its opening into L. Jorzec and thereby the monthly mean surface inflow in this profile were known, so the monthly mean unit

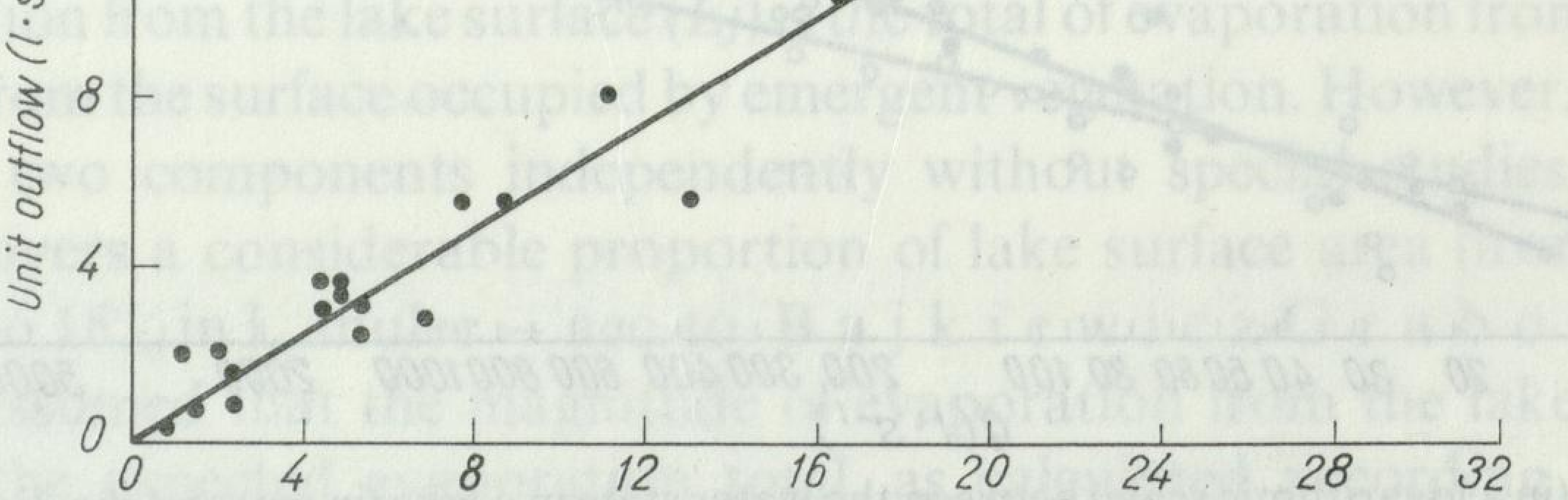

Fig. 4. Relationship between unit run-off from the entire river Baranowska Struga watershed (b) and the unit run-off from its upper part (b$_1$) (see Fig. 1)

discharge in the upper part of the basin of this stream could be read from the relationship plotted earlier (Fig. 4). The above values were used for the determination of the monthly inflow to the lakes from their immediate basins. The areas of the immediate basins of the lakes under study have been given in the paper Bajkiewicz-Grabowska (1985).

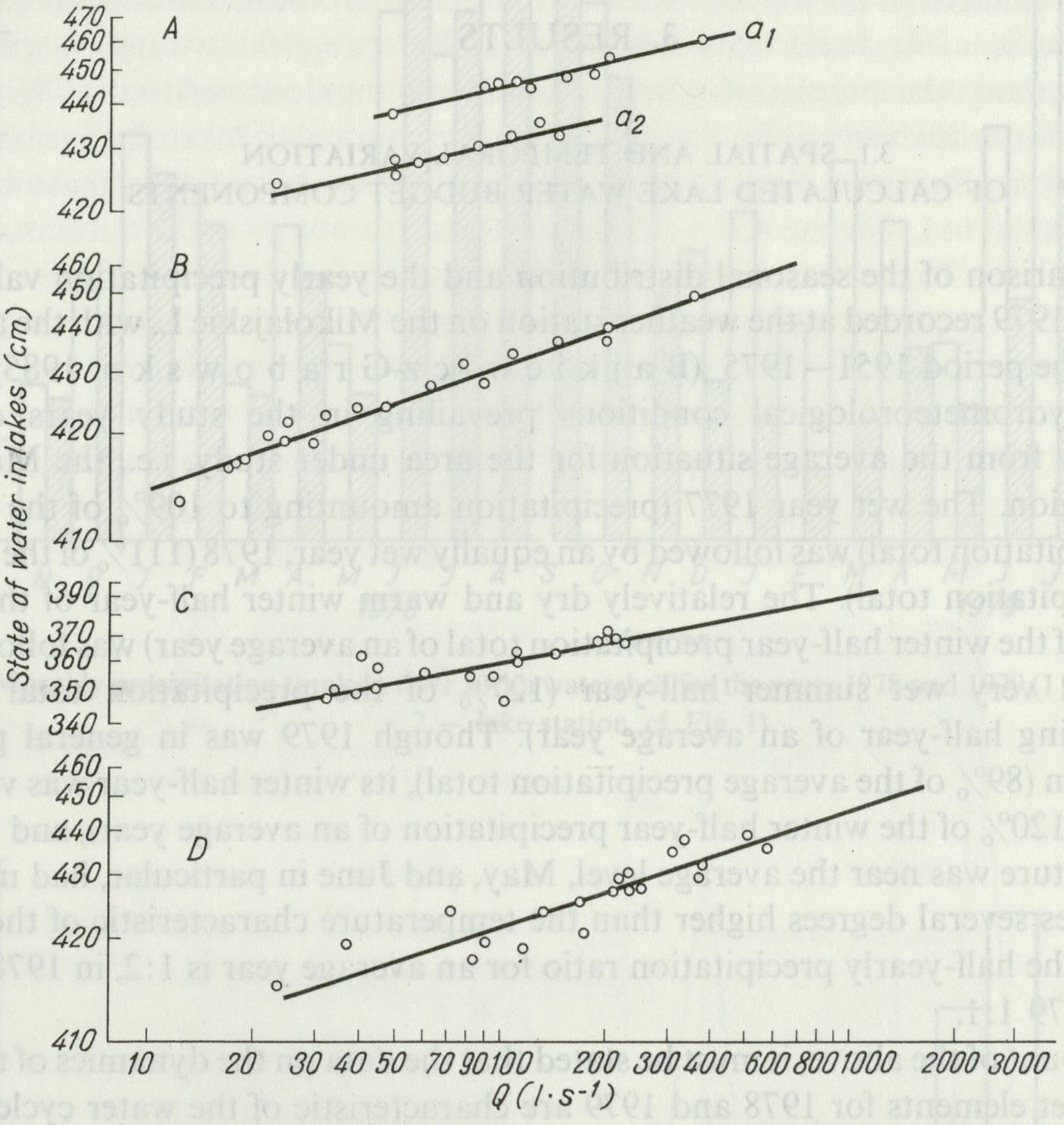

Fig. 5. Relationship (in a logarithmic scale) between the water state in a lake (in cm) and the discharge rate of the river Jorka flowing out of a lake (in $l \cdot s^{-1}$)

A — L. Majcz Wielki, B — L. Inulec, C — Głębokie L., D — L. Jorzec, a_1 — upper gate on the outflow to the Krutynia river, a_2 — lower gate on the outflow to the Krutynia river (Fig. 1, hydrometric profile no. 1)

In the calculation of the monthly mean river outflow from the lakes (*Hwrz*) a procedure similar to that employed for the assessment of the monthly inflow to them was used. A graphical representation has been plotted (Fig. 5) of the relationship between the measured values of discharge at the outlet from the lake (Fig. 1) and the water states in it on the day of measurement. Subsequently, on the basis of a known mean monthly water state in the lake and the relationship curve the water discharge corresponding to it was established and adopted as the monthly mean water discharge of the r. Jorka at the outlet from the lake.

Lake retention (*ΔRj*) was determined on the basis of lake water surface state variations read from lake gauges (Fig. 1).

Underground feeding (*ΔZpd*) was computed by using budget equations set up for the particular lakes. It is the total of supply with subsurface, and possibly with underground waters.

3. RESULTS

3.1. SPATIAL AND TEMPORAL VARIATION OF CALCULATED LAKE WATER BUDGET COMPONENTS

A comparison of the seasonal distribution and the yearly precipitation values for 1977, 1978, 1979 recorded at the weather station on the Mikołajskie L. with the average values for the period 1951 – 1975 (Bajkiewicz-Grabowska 1985) shows that the hydrometeorological conditions prevailing in the study years differed significantly from the average situation for the area under study, i.e., the Masurian climatic region. The wet year 1977 (precipitation amounting to 109% of the annual mean precipitation total) was followed by an equally wet year, 1978 (111% of the annual mean precipitation total). The relatively dry and warm winter half-year of that year (only 80% of the winter half-year precipitation total of an average year) was followed by a cool and very wet summer half-year (127% of the precipitation total of the corresponding half-year of an average year). Though 1979 was in general poor in precipitation (89% of the average precipitation total), its winter half-year was very wet and frosty (120% of the winter half-year precipitation of an average year), and though air temperature was near the average level, May, and June in particular, had monthly temperatures several degrees higher than the temperature characteristic of these two months. If the half-yearly precipitation ratio for an average year is 1:2, in 1978 it was 1:3, and 1979 1:1.

On account of the above, it must be stated that the data on the dynamics of the lake water budget elements for 1978 and 1979 are characteristic of the water cycle in wet years, and not in average years for the area under study.

A comparison of seasonal variations in precipitation at two stations representing the woodland and the lake parts (Fig. 1) of the basin shows greater precipitation totals at the former station: by 7% in 1978 and by 50% in 1979 than at the latter station, although the seasonal variation was very similar (Fig. 6).

Changes in the monthly totals of free-surface evaporation from the lakes in 1978 and 1979 are typical of the climatic region (Fig. 7). A rise in air temperature causes an increase in evaporation from the lake surface, the highest rate of which occurs in the summer (May – June). In July a continuous fall of evaporation totals begins down to the lowest level in the winter (December – January). Because of a fairly high circadian air temperature in the May and June of 1979, the evaporation totals for the two months were greater by 70% and 100% than the evaporation totals for the same months in 1978 (Fig. 7).

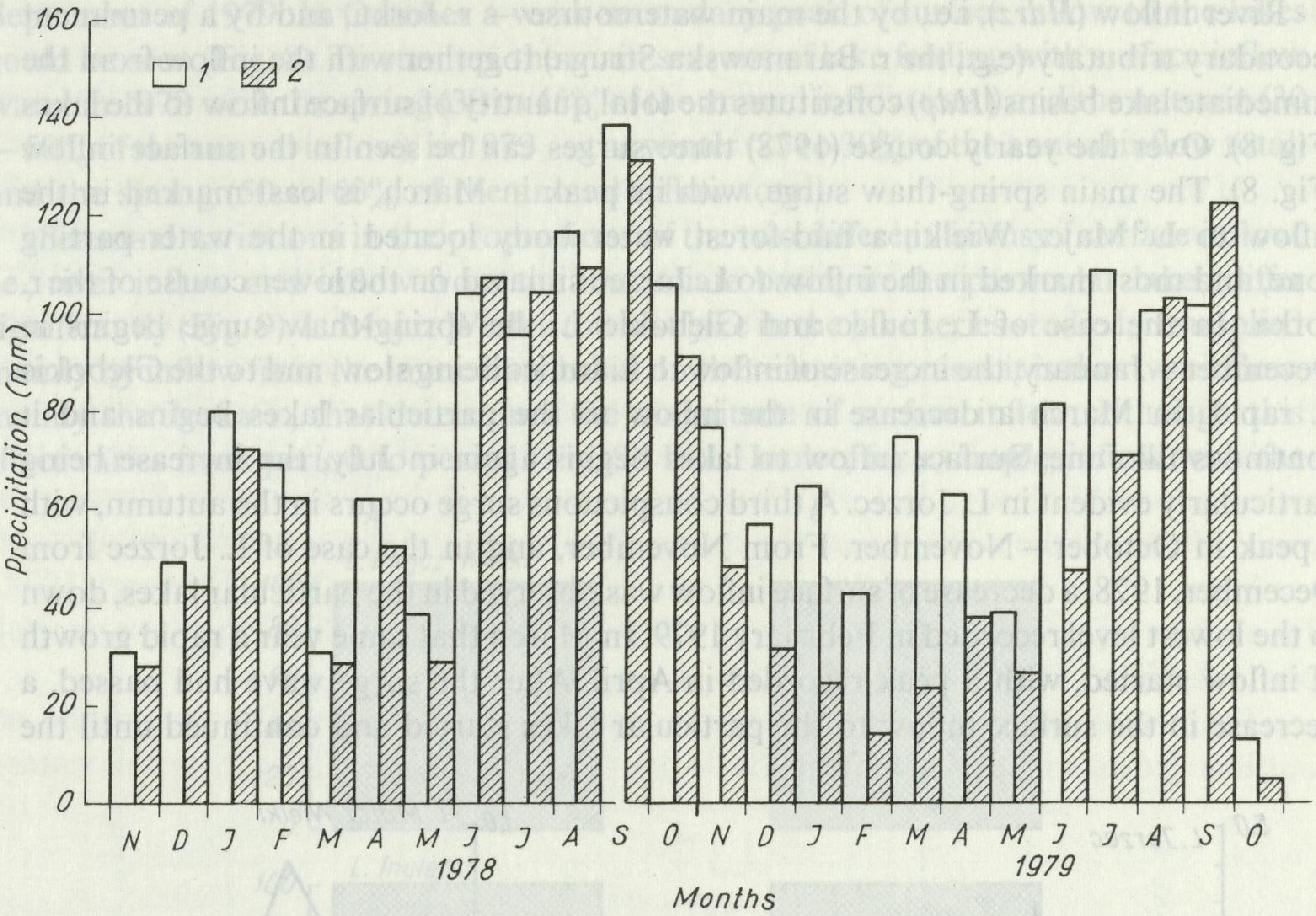

Fig. 6. Monthly precipitation totals in river Jorka watershed for the years 1978 and 1979 (1 – forest station, 2 – lake station, cf. Fig. 1)

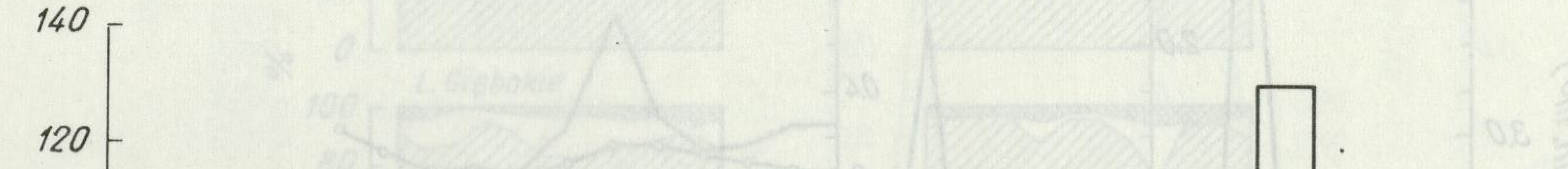

Fig. 7. Monthly totals of evaporation from the lakes of river Jorka watershed for the years 1978 and 1979

River inflow (*Hdrz*), i.e., by the main watercourse – r. Jorka, and by a permanent secondary tributary (e.g., the r. Baranowska Struga) together with the inflow from the immediate lake basins (*Hdp*) constitutes the total quantity of surface inflow to the lakes (Fig. 8). Over the yearly course (1978) three surges can be seen in the surface inflow (Fig. 8). The main spring-thaw surge, with its peak in March, is least marked in the inflow to L. Majcz Wielki, a mid-forest water body located in the water-parting zone, and most marked in the inflow to L. Jorzec situated on the lower course of the r. Jorka. In the case of L. Inulec and Głębokie L. the spring-thaw surge begins in December – January, the increase of inflow to L. Inulec being slow, and to the Głębokie L. rapid. In March a decrease in the inflow to the particular lakes begins and it continues till June. Surface inflow to lakes begins again in July, the increase being particularly evident in L. Jorzec. A third conspicuous surge occurs in the autumn, with a peak in October – November. From November, and in the case of L. Jorzec from December, 1978, a decrease of surface inflow was observed in the particular lakes, down to the lowest level recorded in February 1979. In March that same year a rapid growth of inflow started, with a peak recorded in April. After the surge wave had passed, a decrease in the surface inflow to the particular lakes started and continued until the

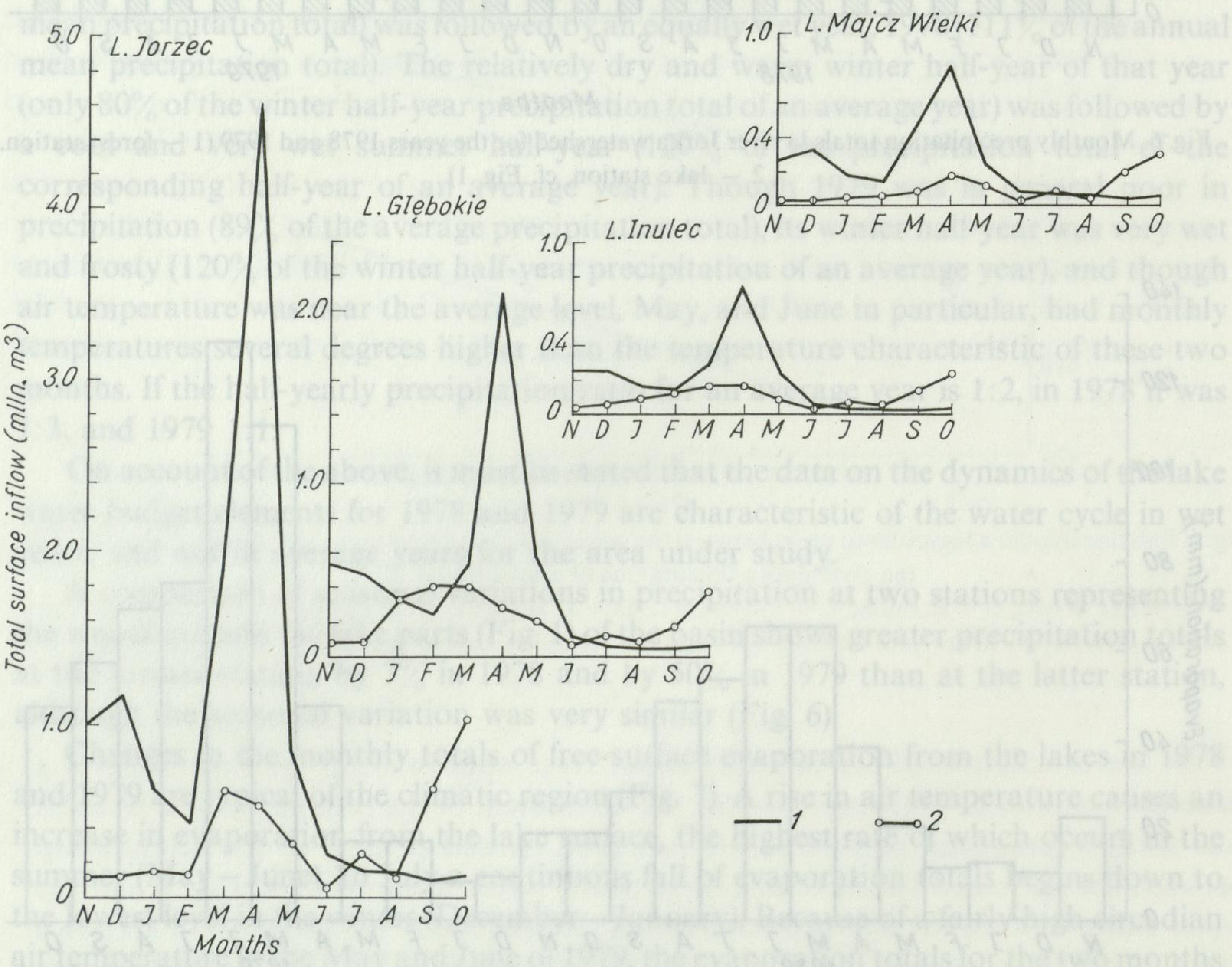

Fig. 8. Seasonal variation in the total surface inflow (the total of river inflow and of inflow from the immediate watershed) to the lakes
1 – 1978, 2 – 1979

September of 1979. In October a weak secondary peak of surface inflow to the lakes could be seen (Fig. 8). To sum up, the main seasons of lake feeding with surface inflow water in 1978 were the spring (30 to 45% of the annual inflow total) and the autumn (30 – 50% of the annual inflow); in 1979 – the winter (25 to 30% of the annual inflow total) and the spring (50 to 60% of the annual inflow total).

Seasonal variations in the proportions of the two different forms of surface inflow, i.e., river inflow and inflow from the immediate basin, in the particular lakes differ significantly (Fig. 9). L. Majcz Wielki, the first lake in the lake series studied, is supplied mainly by inflow from the immediate basin. In the remaining cases it is the river inflow, mainly the Jorka r., that determines the magnitude of surface inflow, although this effect varies from period to period (Fig. 9). In L. Inulec, for example, inflow with the

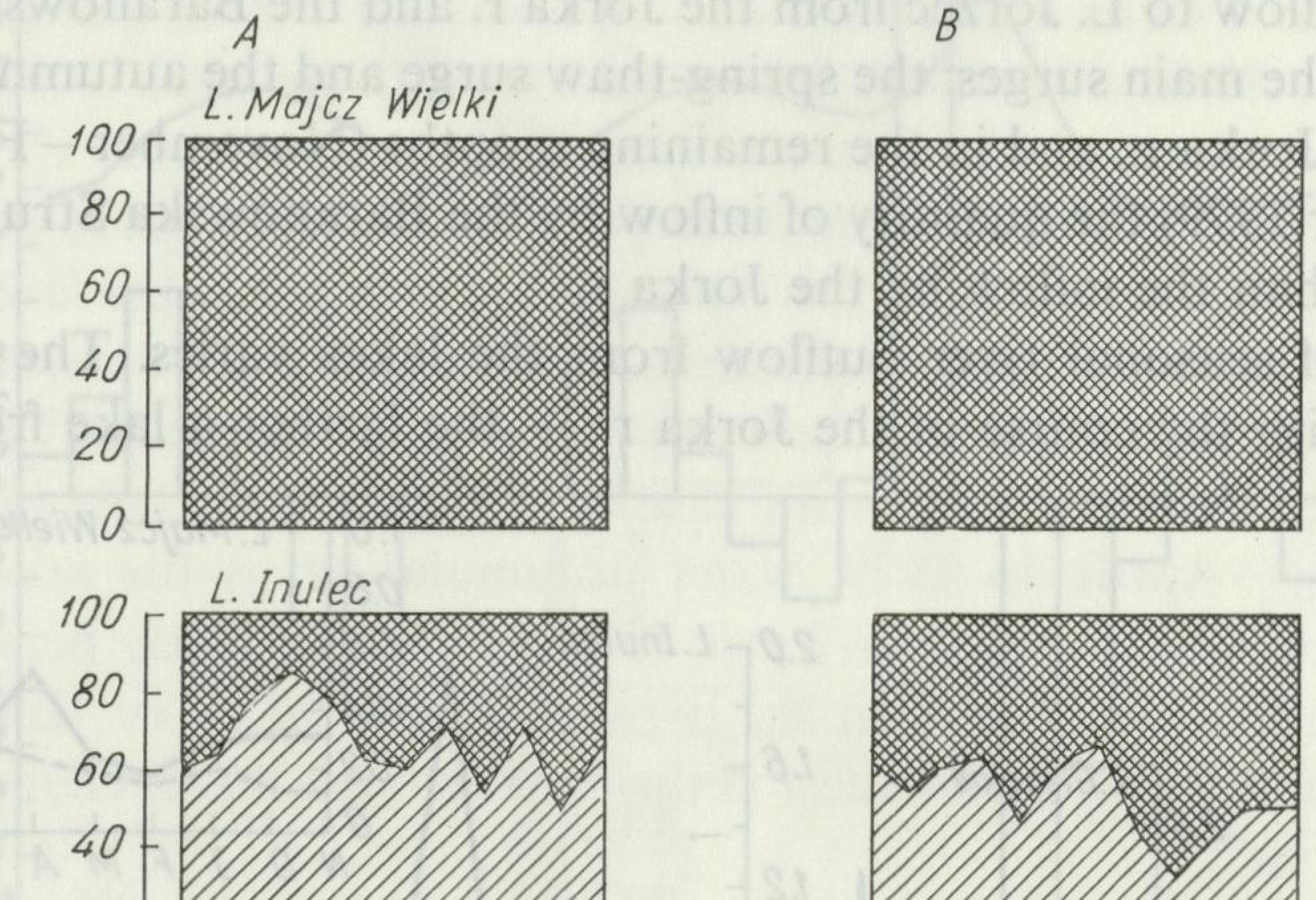

Fig. 9. Seasonal variation in the percentage contribution of the different sources to the total surface inflow to the lakes

A – 1978, B – 1979, 1 – inflow with river Jorka, 2 – inflow from the immediate watershed, 3 – inflow by secondary streams

Jorka r. represents the main contribution to the total inflow only during the spring-thaw surges, whereas in the other seasons only half of the total inflow is contributed by the r. Jorka and the other half is the inflow from the immediate basin of the lake. Surface inflow to Głębokie L. is only supplied by the Jorka r. which in all months feeds over 80% of the total surface inflow to the lake. Feeding from the immediate basin and from the basin of L. Płociczno which is small (0.89 km^2) (Fig. 1) is of low magnitude. There are no clear surges in this inflow, its rate being stable, and it contributes jointly 4 to 13% of the surface inflow (Fig. 9). The quantity of surface inflow to L. Jorzec depends on two permanent watercourses: the main one – the Jorka r., and a secondary one – the Baranowska Struga r. (Fig. 1). The proportion of supply from the immediate basin is small, amounting to 2% of the total inflow to the lake (Fig. 9). The course of the culmination of inflow to L. Jorzec from the Jorka r. and the Baranowska Struga r. is concordant, but the main surges: the spring-thaw surge and the autumn-rainfall surge are higher in the Jorka r., and in the remaining months (November – February 1978, June – November 1979) the quantity of inflow by the Baranowska Struga r. is several per cent higher than the inflow by the Jorka r.

The course of seasonal river outflow from the lakes varies. The magnitude of outflow grows with the course of the Jorka r. – the farther a lake from the water-

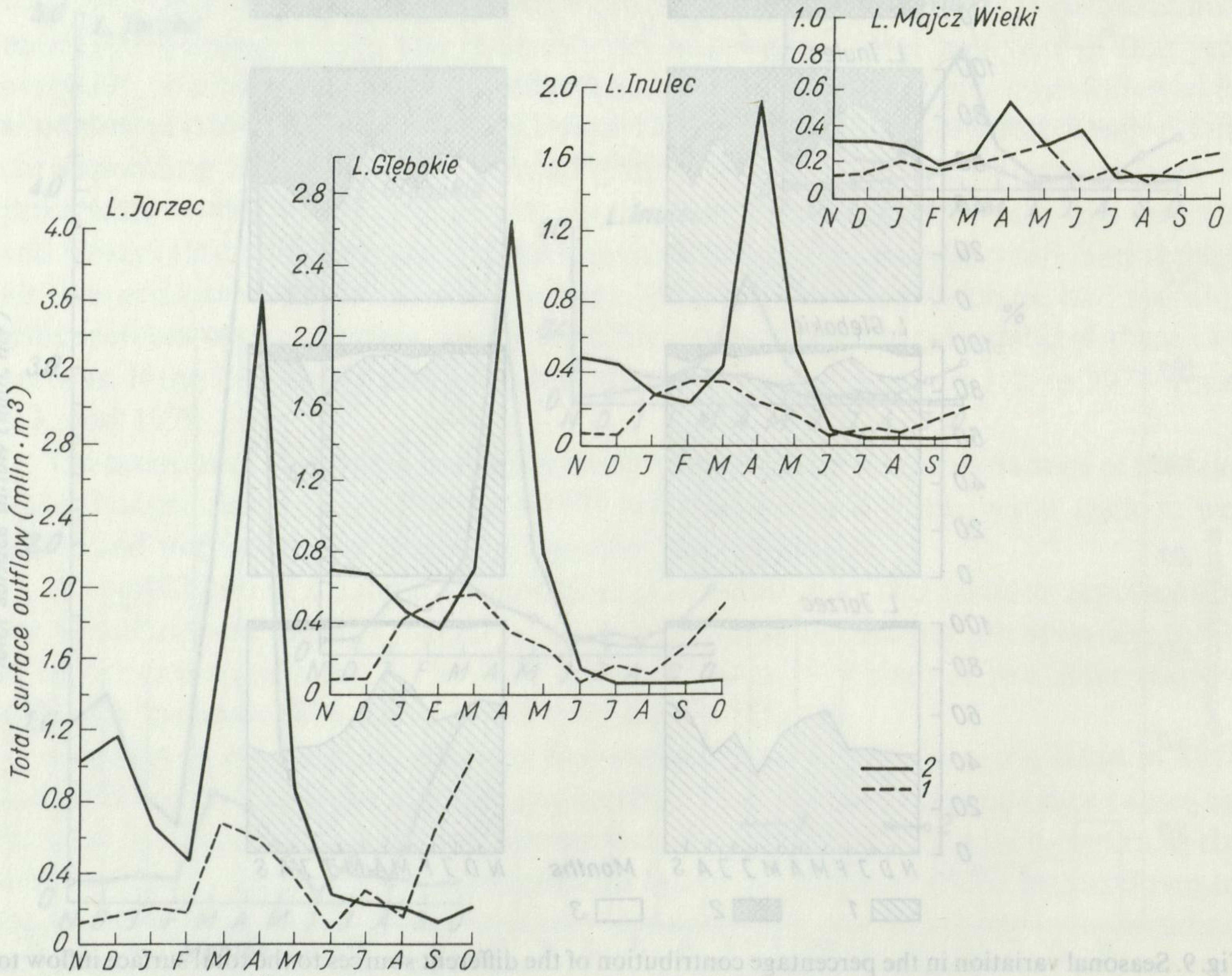

Fig. 10. Seasonal variation of river outflow from the lakes
1 – 1978, 2 – 1979

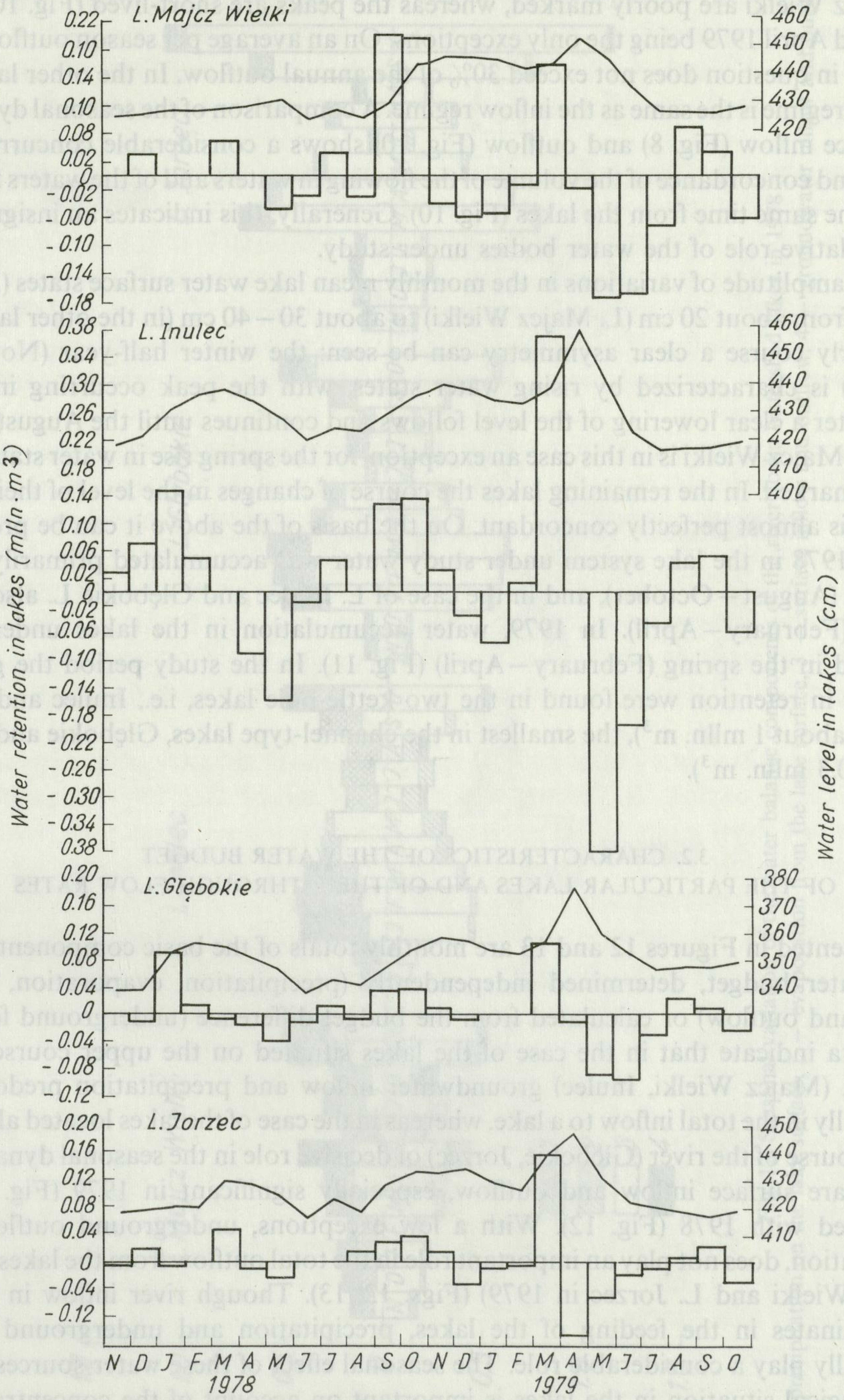

Fig. 11. Seasonal variation of the lake storage (in mlln. m^3) during the balance period, and mean monthly water states in the lakes (in cm)

-parting zone, the larger the volume of inflow. Seasonal variations in the outflow from L. Majcz Wielki are poorly marked, whereas the peaks are short-lived (Fig. 10), May 1978 and April 1979 being the only exceptions. On an average per season outflow from the lake in question does not exceed 30% of the annual outflow. In the other lakes the outflow regime is the same as the inflow regime. A comparison of the seasonal dynamics of surface inflow (Fig. 8) and outflow (Fig. 10) shows a considerable concurrence of surges and concordance of the volume of the flowing in waters and of the waters flowing out at the same time from the lakes (Fig. 10). Generally, this indicates an insignificant accumulative role of the water bodies under study.

The amplitude of variations in the monthly mean lake water surface states (Fig. 11) ranged from about 20 cm (L. Majcz Wielki) to about 30–40 cm (in the other lakes). In the yearly course a clear asymmetry can be seen: the winter half-year (November –April) is characterized by rising water states, with the peak occurring in April, whereafter a clear lowering of the level follows and continues until the August lowest level. L. Majcz Wielki is in this case an exception, for the spring rise in water state in it is faintly marked. In the remaining lakes the course of changes in the level of their water surface is almost perfectly concordant. On the basis of the above it can be presumed that in 1978 in the lake system under study water was accumulated primarily in the autumn (August–October), and in the case of L. Inulec and Głębokie L. also in the winter (February–April). In 1979, water accumulation in the lakes under study occurred in the spring (February–April) (Fig. 11). In the study period the greatest changes in retention were found in the two kettle-hole lakes, i.e., Inulec and Majcz Wielki (about 1 mlln. m^3), the smallest in the channel-type lakes, Głębokie and Jorzec (about 0.3 mlln. m^3).

3.2. CHARACTERISTICS OF THE WATER BUDGET OF THE PARTICULAR LAKES AND OF THEIR THROUGH-FLOW RATES

Presented in Figures 12 and 13 are monthly totals of the basic components of the lake water budget, determined independently (precipitation, evaporation, surface inflow and outflow) or calculated from the budget difference (underground feeding). The data indicate that in the case of the lakes situated on the upper course of the Jorka r. (Majcz Wielki, Inulec) groundwater inflow and precipitation predominate seasonally in the total inflow to a lake, whereas in the case of the lakes located along the lower course of the river (Głębokie, Jorzec) of decisive role in the seasonal dynamics of waters are surface inflow and outflow, especially significant in 1979 (Fig. 13), as compared with 1978 (Fig. 12). With a few exceptions, underground outflow, like evaporation, does not play an important role in the total outflow from the lakes (e.g., L. Majcz Wielki and L. Jorzec in 1979) (Figs. 12, 13). Though river inflow in general predominates in the feeding of the lakes, precipitation and underground supply seasonally play a considerable role. The seasonal effect of these water sources on the hydrological situation in the lakes is important on account of the concentration of different forms of matter present in them. For instance, by contrast to the surface waters, ground waters "dilute" the waters of L. Majcz Wielki, particularly in summer

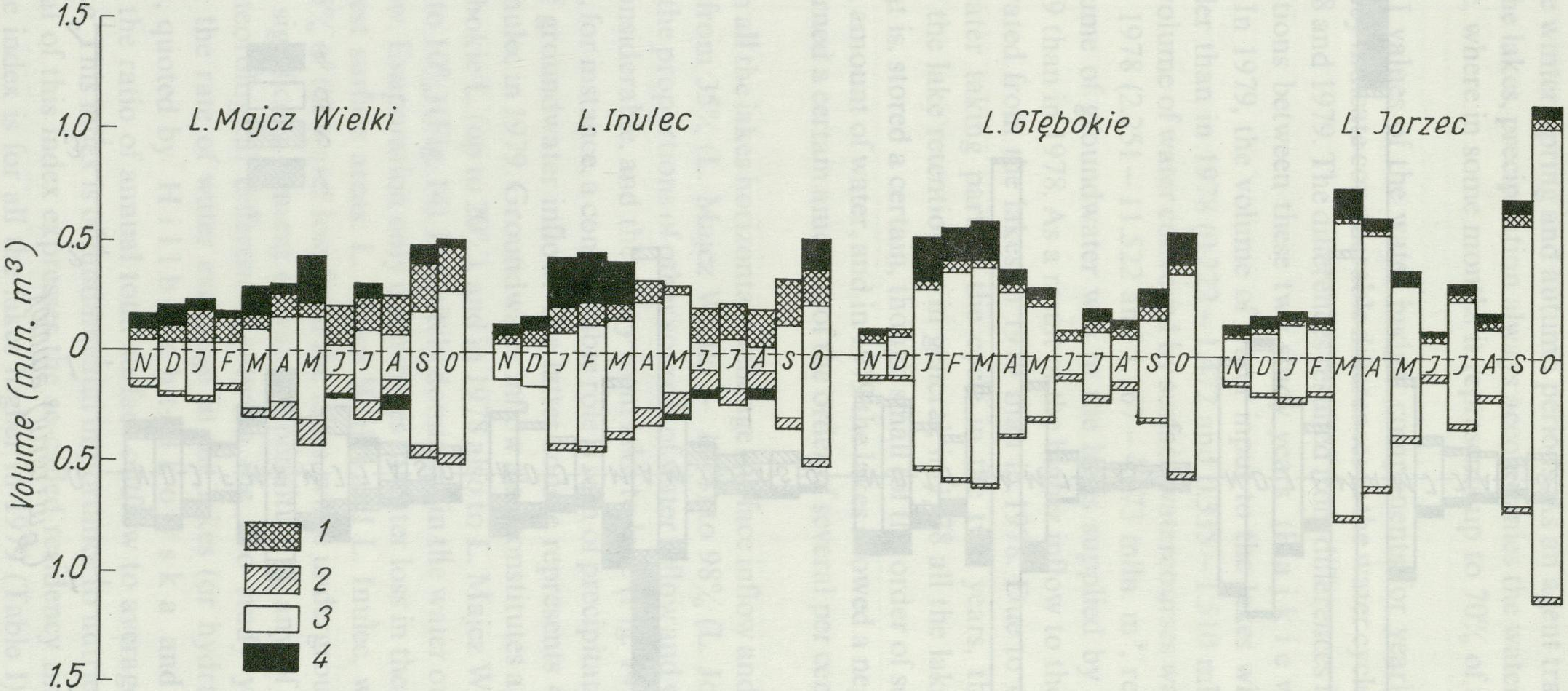

Fig. 12. Seasonal variation of the water balance components of the river Jorka watershed lakes in 1978
1 – precipitation on the lake surface, 2 – evaporation from the lake surface, 3 – surface inflow and outflow, 4 – groundwater inflow and outflow

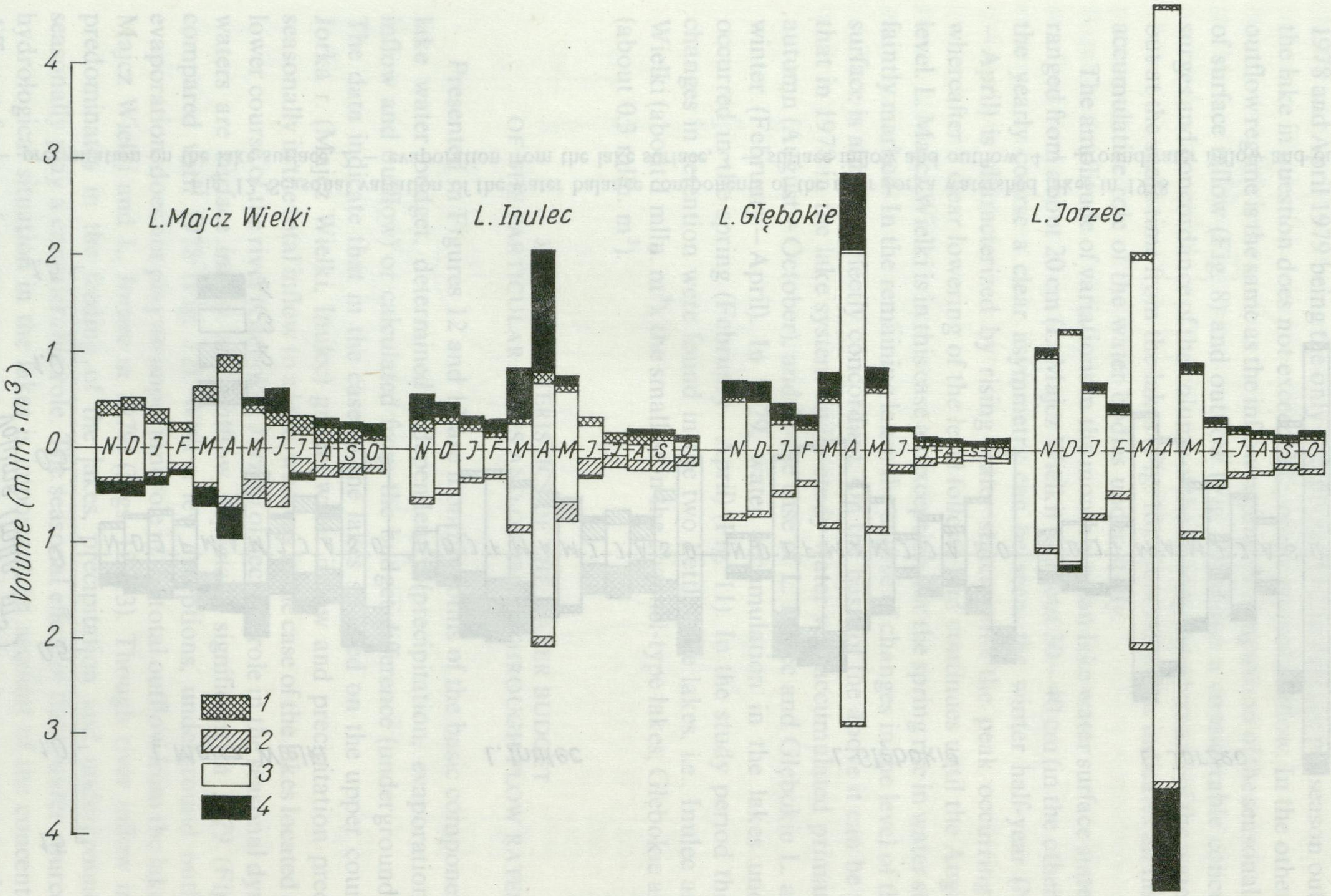

Fig. 13. Seasonal variation of the water balance components of the river Jorka watershed lakes in 1979
1 – precipitation on the lake surface, 2 – evaporation from the lake surface, 3 – surface inflow and outflow, 4 – groundwater inflow and outflow

(they represent up to 30% of the waters fed into the lake), of Głębokie L. mainly in spring. In L. Inulec water "dilution" with ground waters seems to be highest and most durable in the winter, spring and autumn periods. As an agent transporting water and matter into the lakes, precipitation always accompanies the waters of L. Majcz Wielki and L. Inulec, where in some months it represents up to 70% of the waters supplying these lakes.

In Table I values of the water budget components for yearly periods have been presented. They indicate considerable differences in the water cycle in the lakes between the years 1978 and 1979. The differences resulted from differences in the hydrometeorological conditions between these two study years (Bajkiewicz-Grabowska 1985). In 1979, the volume of water input to the lakes with precipitation was slightly smaller than in 1978 (0.222 – 1.472 and 0.335 – 1.510 mlln. m^3, respectively), whereas the volume of water conveyed by surface watercourses was 2 – 3 times as large in 1979 as in 1978 (2.251 – 11.522 and 1.167 – 4.073 mlln. m^3, respectively) (Table I). Also the volume of groundwater was in the lakes supplied by underground inflow higher in 1979 than in 1978. As a result of the higher inflow to the lakes in 1979, more water evaporated from the lakes in 1979 than in 1978. Due to the differences in the volume of water taking part in the cycle in the two years, there were significant differences in the lake retention – in general, in 1978 all the lakes showed a positive retention, that is, stored a certain, though small (of the order of several per cent of the budget total), amount of water, and in 1979 the lakes showed a negative retention, that is to say, returned a certain amount, of the order of several per cent of the budget total, of water.

Though in all the lakes horizontal exchange (surface inflow and outflow) dominates, representing from 35% (L. Majcz Wielki – 1978) to 98% (L. Jorzec – 1979) of the budget total, the proportions of other sources of water inflow and ways of water loss are sometimes considerable, and they vary from lake to lake (Fig. 14). In L. Majcz Wielki and L. Inulec, for instance, a considerable role is seen of precipitation in the total water income, or of groundwater inflow. The latter source represents 44% of all sources of inflow to L. Inulec in 1979. Groundwater inflow also constitutes a permanent source of inflow to Głębokie L. (up to 20%), and in 1978 also to L. Majcz Wielki (up to 15%) and L. Jorzec (up to 10%) (Fig. 14). Definitely dominant in the water outflow from the lakes is river outflow. Evaporation only contributes to water loss in the case of the two lakes with the largest surface areas: L. Majcz Wielki and L. Inulec, where it accounts for about 15 – 25% of the water loss from the lakes, while underground outflow does not seem to be a significant element of water expenditure in any of the lakes studied.

Hydrometeorological differences between the two study years brought about differences in the rate of water exchange in the lakes (or hydraulic loading acc. to Vollenweider, quoted by Hillbricht-Ilkowska and Ławacz 1983), measured by the ratio of annual total surface outflow to average lake volume in the particular lake. This index is of fundamental importance to nutrient retention in lakes. The reciprocal of this index expresses the so-called residency time of water in years.

The above index is for all the lakes higher in 1979 (Table I) than in 1978, being sometimes twice as high, which indicates that in 1979 the through-flow rate of the lakes

Table I. Yearly water budget of the river Jorka watershed lakes for the years 1978 and 1979

Lake and year	Units	Precipitation on lake surface Pj	Evaporation from lake surface Ej	Surface inflow to lake $Hdrz$	Outflow from lake Hw	Change in storage Rj	Ground-water feeding $+Zpdz$	Ground-water outflow $-Zpdz$	Lake volume (mlln. m^3) Vj	Water exchange rate	
										hydraulic load $Hw:Vj$	residency time of water (years)
Majcz Wielki	mlln. m^3	1.510	0.655	1.167	2.269	+0.394	0.641	–	9.86	0.23	4.3
1978	mm	917	403	685	1368	+220	389	–			
	mlln. m^3	1.472	1.094	2.739	3.143	−0.445	–	0.419	11.2	0.28	3.6
1979	mm	819	618	1394	1674	−240	–	161			
Inulec	mlln. m^3	1.348	0.627	1.189	2.318	+0.354	0.762	–	7.45	0.31	3.2
1978	mm	856	403	728	1410	+220	449	–			
	mlln. m^3	0.858	0.981	2.251	4.724	−0.249	2.347	–	7.78	0.60	1.7
1979	mm	548	618	1231	2528	−160	1207	–			
Głębokie	mlln. m^3	0.392	0.182	2.619	3.563	+0.093	0.827	–	5.23	0.68	1.5
1978	mm	855	403	5654	7687	+200	1781	–			
	mlln. m^3	0.248	0.284	5.089	7.036	−0.104	1.879	–	5.40	1.30	0.8
1979	mm	548	618	10355	14330	−220	3825	–			
Jorzec	mlln. m^3	0.335	0.157	4.073	4.629	+0.083	0.461	–	2.08	2.22	0.4
1978	mm	856	403	9969	11374	+00	1152	–			
	mlln. m^3	0.222	0.250	11.522	10.814	−0.083	–	0.763	2.31	4.68	0.2
1979	mm	548	618	25394	24149	−200	–	–			

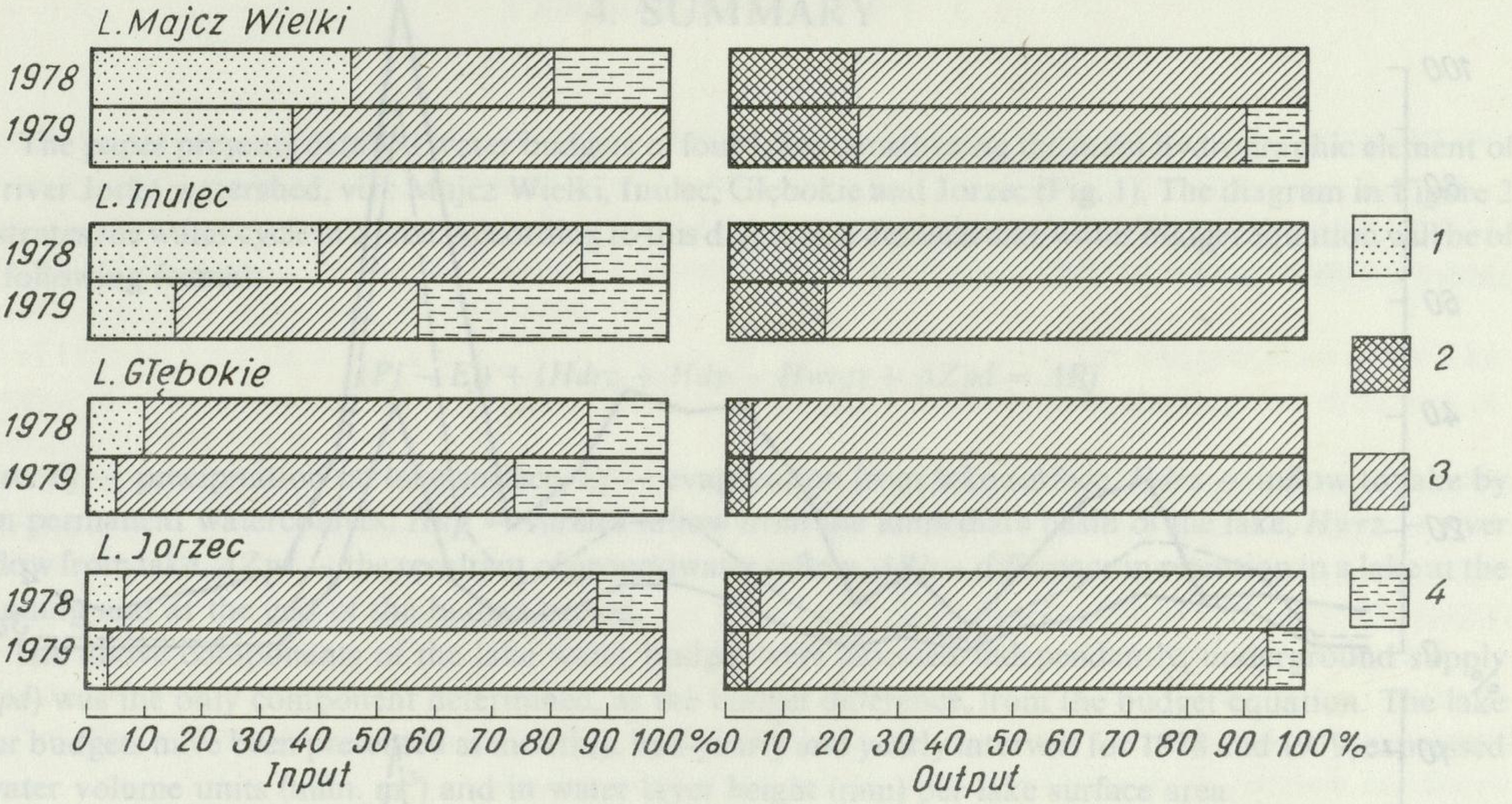

Fig. 14. Percentage contribution of different sources of water to the yearly balance of the river Jorka watershed lakes
1 – precipitation on the lake surface, 2 – evaporation from the lake surface, 3 – surface inflow and outflow, 4 – groundwater inflow and outflow

doubled. The index decreases with decreasing distance between the lake and the water-parting zone, which is natural as the proportion of horizontal exchange drops as the distance from the water-parting decreases (Mikulski 1967). In the case of L. Majcz Wielki, lying in the upper course of the Jorka r., on an average 3–4 years are needed for a complete exchange of the water (differences between 1978 and 1979 were relatively small), whereas in L. Jorzec, situated on the lower course of the Jorka r., a complete exchange of the water required in 1978 about half-a-year, and 2–3 months in 1979, differences between these two years were thus significant.

The lakes analysed also differed in the amplitude of seasonal changes in the exchange rate, although their course is similar in all the lakes (Fig. 15). The water exchange rate in the successive months was calculated as a monthly river outflow to monthly mean lake water volume ratio, and in the case of the deeper lakes (L. Majcz Wielki and Głębokie L.) also to epilimnion volume (to the depth of 8 m). The latter quantity better expresses the rate of horizontal exchange in a deeper lake because it refers to the surface layer, and it is this layer that is subject, more than any other, to exchange (so-called effective water exchange) (Fig. 15).

Following the seasonal variations in the water exchange rate in the study lakes, one can notice a clear increase in its value with the growing distance down the course of the Jorka r. (Fig. 15). In the winter of 1978 water exchange in the study lakes was very low – of the order of 1–2% in lake Inulec, Głębokie, and about 10% in L. Jorzec. A growth in exchange rate occurred in the spring, this growth being small in the case of L. Inulec (4–5%), greater in Głębokie L. (up to 10%) and considerable in L. Jorzec (up to 30%). The months June–August of 1978 were the period in which water exchange in the

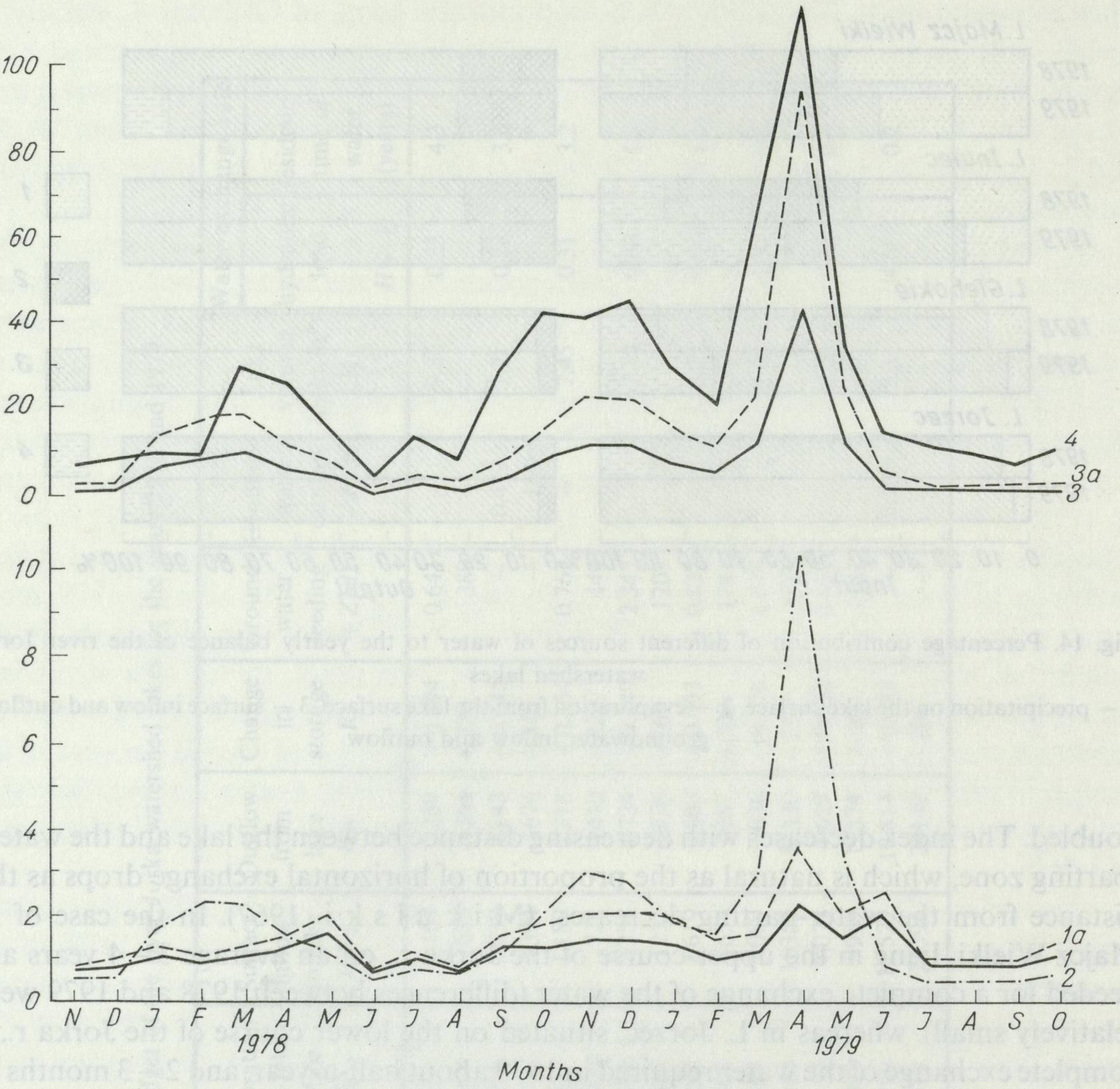

Fig. 15. Seasonal variation of the water exchange rate (the river outflow to lake volume ratio) in the river Jorka watershed lakes

1 – L. Majcz Wielki, 2 – L. Inulec, 3 – Głębokie L., 4 – L. Jorzec, 1a, 3a – the so-called effective exchange, that is to say, the outflow to epilimnion volume ratio in L. Majcz Wielki and in Głębokie L.

lakes was again small: as low as 1% in L. Inulec, Głębokie L., slightly more – 5 – 10% in L. Jorzec. From September on, as a result of an increased water outflow, the rate of water exchange rose in all the lakes: a little, again, in L. Inulec (up to 6%), slightly more in Głębokie L. (up to 25%) and considerably in L. Jorzec (up to 45%). A high rate of exchange persisted until December; in January 1979 it fell and rose again rapidly from March 1979 on, in all the lakes. The peak of the exchange rate (lake through-flow rate) occurred in April and amounted to 21% in L. Inulec, 45% in Głębokie L., and as much as 115% in L. Jorzec. From June till the end of 1979 again only a small amount of water was subject to exchange – in L. Inulec and Głębokie L. about 1 – 2%, in L. Jorzec about 10%. Different from the above scheme is the first lake of the system discussed, i.e., L. Majcz Wielki. In 1978 and 1979, in this lake the water exchange rate remained at a level of 2 – 3%, and only in April and June 1979 did it slightly rise, up to 4%.

4. SUMMARY

The paper presents detailed water budgets of four lakes constituting the main hydrographic element of the river Jorka watershed, viz.: Majcz Wielki, Inulec, Głębokie and Jorzec (Fig. 1). The diagram in Figure 2 illustrates the water cycle in a lake. According to this diagram, a detailed lake water budget equation will be of the following format:

$$(Pj - Ej) + (Hdrz + Hdp - Hwrz) + \Delta Zpd = \Delta Rj$$

where: Pj – precipitation on lake surface, Ej – evaporation from lake surface, $Hdrz$ – inflow to lake by main permanent watercourses, Hdp – surface inflow from the immediate basin of the lake, $Hwrz$ – river outflow from lake, ΔZpd – the resultant of groundwater inflow, ΔRj – difference in retention in a lake at the beginning and at the end of the budget period.

The above components of the lake water budget were assessed independently; underground supply (ΔZpd) was the only component determined, as the budget difference, from the budget equation. The lake water budgets have been presented at monthly, half-yearly and yearly intervals for 1978 and 1979, expressed in water volume units (mlln. m^3) and in water layer height (mm) per lake surface area.

Monthly totals of precipitation on the lake surface were obtained from direct measurements in the basin (Fig. 1) – for L. Majcz Wielki from station no. 1, for lakes Inulec, Głębokie and Jorzec from station no. 2.

Monthly totals of evaporation from lake surface were calculated according to Dawidow's formula:

$$Ep = 15d^{0.8}(1 + 0.125w_{1000})$$

where: Ep – monthly mean evaporation total, d – monthly mean air humidity deficit, w_{1000} – monthly mean wind velocity 10 m above ground.

River inflow to lakes was determined on the basis of plotted curves of the relationship between measured water discharges of permanent watercourses (Fig. 1) and water states in a lake, corresponding to the measurement dates (Fig. 3); a similar procedure was used for the assessment of the volume of outflow from the lakes (Fig. 5).

Inflow from the immediate basins of the lakes was calculated on the basis of the value of unit discharge in the basin. In this case the analogy method was used, based on the assumption that the unit discharge in the upper part of the basin of the Baranowska Struga r. (Fig. 1 no. Vb_1) should be similar to that found in the immediate basins of the lakes (Fig. 1 no. Ia, IIa, IIIa, IVa) similar to it hydrographically and in respect of the land-use structure. Determination of the unit discharge value in the upper basin of the Baranowska Struga r. was based on the correlation between the magnitude of the unit discharge of this part of the basin and the corresponding values of unit discharge for the whole watershed of the Baranowska Struga r. (Fig. 4).

Lake retention was assessed on the basis of water surface state variations in the lakes, read from lake gauges (Fig. 1).

Seasonal course of precipitation in the budget years has been presented in Figure 6, of evaporation in Figure 7, seasonal changes in total surface inflow (total of river inflow and of inflow from the immediate basin) to lakes in Figure 8, whereas seasonal variations in the per cent contribution of the different sources of inflow to the total surface inflow to the lakes have been presented in Figure 9, seasonal variation in river outflow from the lakes in Figure 10, and seasonal changes in lake retention in Figure 11.

Water budget component values for yearly periods have been summarized in Table I, whereas their course at monthly intervals has been illustrated in Figures 12 and 13. Figure 14 presents the per cent contribution of the different water sources to the annual budget of the r. Jorka watershed lakes.

Seasonal variations in the water exchange rate (the river outflow from lake to lake volume ratio) in the r. Jorka watershed lakes have been presented in Figure 15. Here also, in the case of the deeper lakes (Majcz Wielki and Głębokie), the seasonal variation has been illustrated of the so-called effective exchange (the river outflow to epilimnion volume ratio).

5. POLISH SUMMARY

W opracowaniu przedstawiono szczegółowe bilanse wodne 4 jezior stanowiących główny element hydrograficzny dorzecza rzeki Jorki, a mianowicie: Majcz Wielki, Inulec, Głębokie i Jorzec (rys. 1). Schemat obiegu wody w jeziorze ilustruje rys. 2. W myśl tego schematu szczegółowe równanie bilansu wodnego jeziora przyjmie postać:

$$(Pj - Ej) + (Hdrz + Hdp - Hwrz) + \Delta Zpd = \Delta Rj$$

gdzie: Pj – opad na powierzchnię jeziora, Ej – parowanie z powierzchni jeziora, $Hdrz$ – dopływ głównymi ciekami stałymi do jeziora, Hdp – dopływ powierzchniowy z bezpośredniej zlewni jeziora, $Hwrz$ – odpływ rzeczny z jeziora, ΔZpd – wypadkowa zasilania podziemnego, ΔRj – różnica retencji w jeziorze na początku i na końcu okresu bilansowania.

Powyższe składowe bilansu wodnego jezior oceniono niezależnie; jedynie zasilanie podziemne (ΔZpd) określono z równania bilansu jako różnicę bilansową. Bilanse wodne jezior przedstawiono w przedziałach miesięcznych, półrocznych i rocznych dla lat 1978 i 1979 w jednostkach objętości wody (mln m^3) i w wysokości warstwy wody (mm) na powierzchnię zwierciadła jeziora.

Sumy miesięczne opadu na powierzchnię jezior przyjęto na podstawie bezpośrednich pomiarów w zlewni (rys. 1) dla jeziora Majcz Wielki z posterunku nr 1, dla jezior Inulec, Głębokie i Jorzec z posterunku nr 2.

Sumy miesięczne parowania z powierzchni jezior obliczono wg formuły Dawidowa:

$$Ep = 15d^{0.8}(1 + 0{,}125\ w_{1000})$$

gdzie: Ep – średnia miesięczna suma parowania, d – średni miesięczny niedosyt wilgotności powietrza, w_{1000} – średnia miesięczna prędkość wiatru na wysokości 10 m.

Dopływ rzeczny do jezior określono na podstawie sporządzonych zależności graficznych między pomierzonymi wartościami natężenia przepływu dopływów stałych (rys. 1) a stanami wody w jeziorze, odpowiadającymi datom wykonanych pomiarów (rys. 3); podobnie postąpiono przy ocenie wielkości odpływu z jezior (rys. 5).

Dopływ z bezpośredniej zlewni jezior obliczono na podstawie wielkości spływu jednostkowego w zlewni. Wykorzystano przy tym metodę analogii przyjmując, że wartości spływów jednostkowych w górnej części zlewni rzeki Baranowska Struga (rys. 1 nr Vb_1) powinny być zbliżone do tych, jakie występują w bezpośrednich zlewniach jezior (rys. 1 nr Ia, IIa, IIIa, IVa) podobnych do niej pod względem hydrograficznym i o podobnym charakterze użytkowania ziemi. Przy określaniu wielkości spływu jednostkowego w górnej części zlewni rzeki Baranowska Struga wykorzystano zależność korelacyjną między wielkością spływu jednostkowego tej części zlewni a odpowiadającym mu wielkościom spływu jednostkowego z całego dorzecza rzeki Baranowska Struga (rys. 4).

Retencję jeziorną oceniono na podstawie wahań stanów zwierciadła wody w jeziorach odczytywanych z wodowskazów jeziornych (rys. 1).

Sezonowy przebieg opadów w bilansowanych latach prezentuje rys. 6, sum parowania rys. 7, sezonowe zmiany całkowitego dopływu powierzchniowego (suma dopływu rzecznego i dopływu z bezpośredniej zlewni) do jezior rys. 8, przy czym sezonowe zmiany procentowego udziału różnych źródeł dopływu w całkowitym dopływie powierzchniowym do jezior przedstawiono na rys. 9, natomiast zmienność sezonową odpływu rzecznego z jezior na rys. 10 i sezonowe zmiany retencji jeziornej na rys. 11.

Wartości składowych bilansu wodnego dla okresów rocznych zestawiono w tab. I, a przebieg ich w przedziałach miesięcznych zobrazowano na rys. 12 i 13. Procentowy udział różnych źródeł wody w rocznym bilansie jezior dorzecza rzeki Jorki przedstawiono na rys. 14.

Sezonowe zmiany intensywności wymiany wody (stosunek odpływu rzecznego z jeziora do objętości jeziora) w jeziorach dorzecza rzeki Jorki przedstawiono na rys. 15. Tu także, w przypadku jezior głębszych (Majcz Wielki i Głębokie), zilustrowano sezonową zmienność, tzw. wymiany efektywnej (stosunek odpływu rzecznego z jeziora do pojemności epilimnionu).

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