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Diversity of surface outflow from lakes which perform different hydrological functions

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Abstract: The relationships between the hydrographic function of lakes and the features of catchment structure and parameters of the morphometry of lake basins were evaluated using a balance approach. Three types of lakes were distinguished: (1) moderately draining lakes, (2) draining and strongly draining lakes, (3) flow-through lakes. Lake outflow in each of the typological groups is determined by both these factors but in a different way. In flow-through and moderately draining lakes, changes in the area of passive catchment cause opposite changes of outflow. In strongly draining lakes this dependence does not occur, and outflow is proportionate to the size of the total catchment. This shows that draining and strongly draining lakes are the main recipients of waters accumulated in areas without outflow. Draining capacity of lakes is determined also by local geological structures, which constitute basis for a further division of lakes into draining and strongly draining ones.

Key words: hydrological functions of lakes, structure of catchment, hydrology of lakelands, morphometry of lakes

Introduction

The term 'hydrological function' of lakes is defined in various ways. In a systemic approach, hydrological function is expressed in the role that a lake plays in collecting various forms of outflow which appear in the catchment [Drwal 1985]. A less important process here is the subsequent redistribution of water excess in the form of river outflow and evaporation.

In another approach it is equated with the role of lakes in shaping the conditions of water circulation in catchment. In such a case, apart from streams of water inflow, other important elements in the evaluation of the role of lakes in organised outflow systems include also water outlay streams as complementing water balance and determining the actual influence of reservoirs on the water regime of rivers flowing through them [Borowiak 2000]. The diversity of functions performed by lakes is most fully reflected in individual water balances. A reference, similar in interpretation, of the hydrological function of lake to the water balance of the lake catchment can be found in Mikulski [1970].

With the use of the balance approach, an analysis was performed of the relationships between the hydrological function of lakes and natural characteristics of lake catchments as well as morphometric parameters conditioned by different morphogenesis of lake basins. The measures concerning the structure and diversity of catchment, including such characteristics as: relative proportion of active and passive catchment, relative catchment, surface formations (sands, boulder clay, lake sediments and peat), and elements of the structure of land use (woodiness) were assumed to be the leading ones.

Study area

The research covered 18 lakes situated in upper catchments of the main rivers of Eastern Pomerania: the Radunia (8), Łeba (2), Łupawa (1), Słupia (5) and Wieprza (2) (Fig. 1), which are located within the borders of two physical-geographic units, i.e. the Kashubian and Bytów Lakelands. The catchments represent varying geomorphological, hydrological and natural conditions characteristic of watershed areas of young

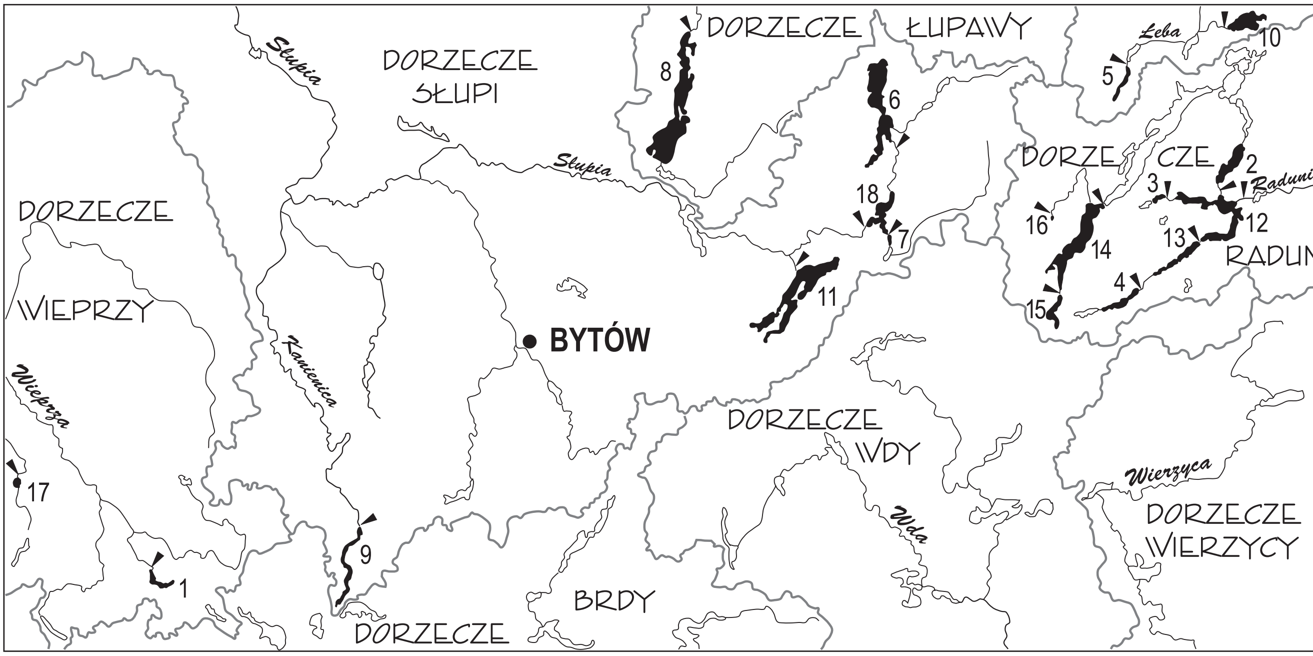

Fig. 1. Distribution of lakes under study (lake numbers according to Table 1). Triangles mark the sites of discharge measurements

Table 1. Morphometric characteristics of the lakes under study and their catchments

No	Lake	Altitude	Area	Volume	Maximum Depth	Mean Depth	Catchment Area	Relative catchment	Schindler's coefficient
		m a.s.l.	ha	×10 m³	m	m	ha	n.d.	m²/m³
1.	Bluj *	157.9	39.8	1979.0	11.3	5.0	1372.2	34.48	6.9
2.	Brodno W. **	160.0	134.1	8823.0	15.7	6.6	14405.0	107.42	16.3
3.	Bukrzyno D. ***	161.0	20.8	915.0	10.8	4.4	490.0	23.56	5.4
4.	Dąbrowskie **	166.2	64.3	4114.6	15.2	6.4	1083.0	16.84	2.6
5.	Długie ***	165.3	49.7	2968.0	11.6	6.0	1802.7	36.42	6.1
6.	Gowidlińskie **	165.6	392.9	30391.0	26.9	7.6	6263.0	15.94	2.1
7.	Guścierz Mały *	162.4	10.1	454.5	8.3	4.5	4520.0	447.52	99.4
8.	Jasień **	112.6	577.2	48048.8	32.2	8.3	7750.0	13.43	1.6
9.	Kamieniczno **	159.0	120.7	11633.2	23.2	9.6	1938.0	16.06	1.7
10.	Łapalickie **	165.0	155.1	15024.5	23.6	9.7	2263.0	14.59	1.5
11.	Mausz **	153.9	459.7	53856.8	45.0	11.7	3173.0	6.90	0.6
12.	Ostrzyckie **	159.0	308.0	20785.2	21.0	6.7	20111.0	65.30	9.7
13.	Patulskie **	159.5	93.6	3606.5	7.8	3.9	2805.0	29.97	7.8
14.	Raduńskie Grn. **	161.3	387.2	60158.7	43.0	15.5	6471.0	16.71	1.1
15.	Stężyckie ***	162.7	61.7	2348.9	11.7	3.8	1663.0	26.95	7.1
16.	Szewinko ***		3.4	44.7	2.8	1.2	361.1	106.2	80.8
17.	Trzcińskie *	127.6	28.6	1813.5	14.4	6.3	1777.7	62.16	9.8
18.	Węgorzyno **	162.4	124.2	6189.6	14.0	5.0	12666.0	101.98	20.5

Lake morphometry according to: *IMGW, **IRS, ***UG glacial lakelands. The location of lakes within areas of formation and organisation of surface outflow systems results in the fact that various hydrological functions performed by them become clearer. The catchments, being adjacent to the Pomeranian watershed, group lakes of various hydrogenesis, which is manifested in their morphometric diversity (Table 1). In terms of the area of water surface, these are small and medium lowland lakes. Depth diversity of the lakes is considerable, including very shallow reservoirs supplied from poor in water near-surface water-bearing horizons (Szewinko – max depth 2.8 m) as well as very deep channel lakes sometimes cutting several water-bearing horizons (Mausz, Upper Raduńskie), whose maximum depths are over 40 m and mean depths over 10 m.

Methods

The basis of the performed hydrological analysis of the reservoirs under study were the results of discharge measurements obtained during the patrol survey performed in hydrological years 2004-2005. Discharge measurements in lakes situated in the upper catchments of the Łeba, Radunia and Słupia were performed at monthly intervals, whereas for lakes of the upper Łupawa and Wieprza at two-month intervals and concerned just one hydrological year 2004. For the purposes of further analysis, mean values of the whole measurement period were used and subjected to statistical analysis using programs of Statistica package. During the measurements of the efficiency of catchments, additional water-gauge measurements were performed and they were the basis to calculate approximate values of annual amplitudes of water stages. The performed analysis of dependences between mean annual amplitudes of water stages and the synthetic measure of water balance of lakes, i.e. outflow increase ratio, dQ (Borowiak, 2000), indicates a close statistical relationship between the two parameters (Fig. 2). Thus, it can be assumed that the measurement results constitute comparable documentation material, despite the heterogeneity of measurement period which was adopted for three reservoirs (Bluj, Jasień, Trzcińskie).

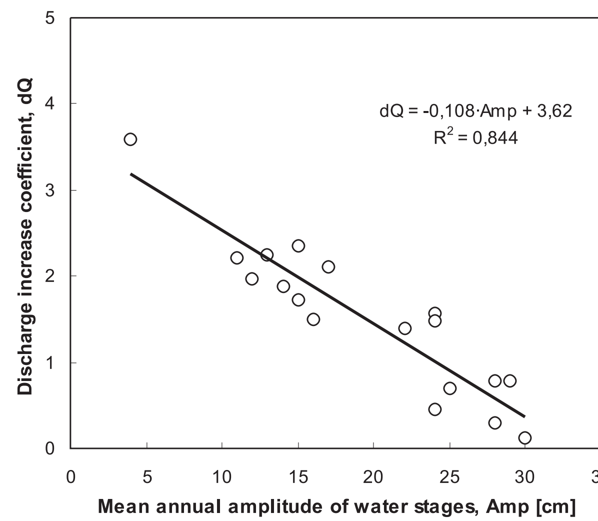

Fig. 2. Dependence between outflow increase ratio and mean amplitude of water stages

Results

All the hydrological parameters of lakes taken into consideration in the study accurately describe the diversity of conditions of water circulation in the lakes under study. The analysis of the main components showed that there are three main factors explaining 93% of differences among lakes. The first one (47.0%) characterises the hydrological efficiency of lake catchment and covers such measures as: outflow index (H) as well as mean (q), minimum (q_{min}) and maximum (q_{max}) specific runoff. The second factor, basically equated with the structure of water balance of lakes, is conditioned by the outflow increase ratio (dQ), inflow from catchment (R), annual amplitude of water stages (AMP) and outflow from lake (D), explains 30.5% of the diversity. The third factor (15.5%) refers mainly to seasonal variability of outflow and is determined by the annual coefficient of specific runoff variability (q_{max} / q_{min}). By means of the enumerated hydrological characteristics the whole number of lakes was divided into three almost homogenous lake groups, using the Ward's cluster analysis method. The characteristics of the structure of water balance of the distinguished lake groups and particular lakes within each group are presented in the diagram (Fig. 3). Each of the distinguished lake groups includes lakes with similar hydrological functions.

The first group embraces lakes of unstable conditions of water exchange (Bluj, Bukrzyno Duże, Dąbrowskie, Długie, Guścierz Mały, Łapalickie, Szewinko, Trzcińskie). These are basically moderately draining lakes (dQ=1.0÷1.5), with small water resources of catchment (q_{min} <3 $l \cdot s^{-1} \cdot km^{-2}$) and high seasonal variability of outflow (q_{max} / q_{min} = 5÷30). The second group includes draining and strongly drain-

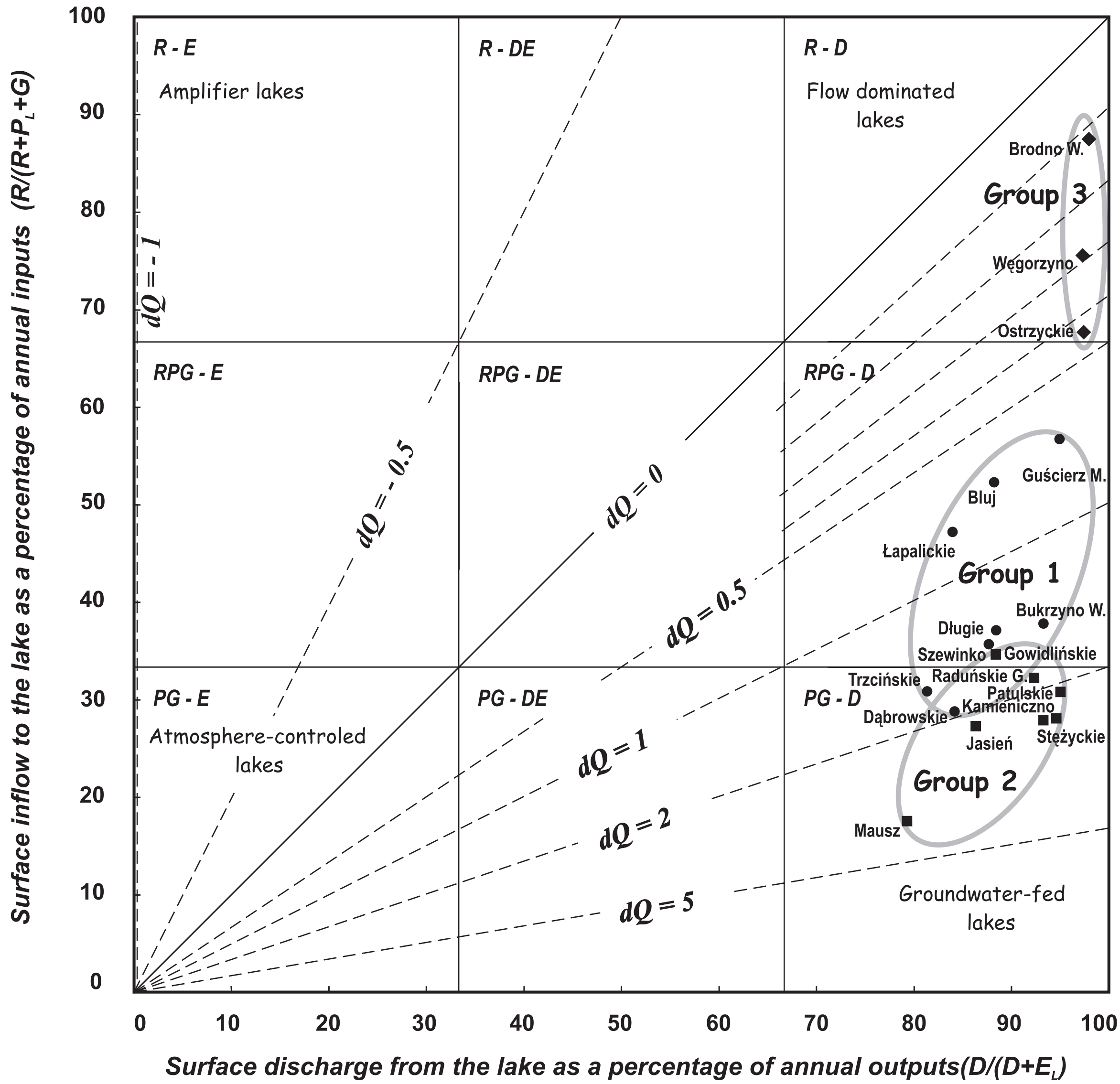

Fig. 3. Structure of water balance of lakes under study

ing lakes (Gowidlińskie, Jasień, Kamieniczno, Mausz, Patulskie, Upper Raduńskie, Stężyckie) with outflow increase ratios dQ >1.5. The catchments of these lakes are characterised by the highest efficiency ($q_{min} > 7$ $l \cdot s^{-1} \cdot km^{-2}$) and seasonal stability of outflow ($q_{max} / q_{min} < 3.5$). The third group comprises flow-through and strongly flow-through lakes that play the role of transit objects in river-lake systems (Brodno Wlk., Ostrzyckie, Węgorzyno). The hydrological efficiency of their catchments is average ($q_{min} = 4 \div 8$ $l \cdot s^{-1} \cdot km^{-2}$), seasonal stability of outflow is high ($q_{max} / q_{min} < 4$), and relative proportion of underground alimentation in the structure of water income is small (dQ <0.5), though in absolute values the inflow can be significant. The characteristics describing the general conditions of water circulation in catchments of individual lake groups are presented in Fig. 4.

The analysis of cause-effect relationships of the diversity of water circulation conditions and natural characteristics of catchments and morphometry of lake basins in the distinguished groups revealed clear regularities and dependences with the hydrographic structure of catchment (proportion of active catchment and areas without outflow) as well as with the morphometry of reservoirs. However, there are no clear relationships between the hydrological measures and chosen components of the environment such as: structure of surface formations or forms of land use.

In small reservoirs of the watershed zone (lakes of the first group) there are strong dependences between the area of active catchment and value of outflow from the lakes. An increase in passive areas (without outflow) contributes to a decrease in outflow. When the proportion of passive areas is about 60-80%, specific runoff from catchments of lakes which maintain the outflow character at least seasonally is just about 2 $l \cdot s^{-1} \cdot km^{-2}$, while with the relative no-outflow character of catchment of about 20%, the unit outflow increases to 8 $l \cdot s^{-1} \cdot km^{-2}$ (Fig. 5a). Another characteristic fact is that with an increase in relative catchment of lakes, unit outflow does not increase (Fig. 5b). This should be attributed to the fact that in watershed areas an increase in total lake catchment area mainly involves an increase in the proportion of passive areas (not included in the surface draining system), which is characteristic of young glacial lakeland areas with initial development of river network. Local conditions, can however, cause deviations from the rule. This means that with a relatively high proportion of passive areas in the total catchment structure (40-50%) outflow can be maintained at a high level as it is the case in Lake Bukrzyno Duże (q=12.5 $l \cdot s^{-1} \cdot km^{-2}$), or the conditions of local under-surface circulation result in the fact that a larger catchment area with a high proportion of areas without outflow does not have to accompanied by a decrease in outflow, as it is observed in Lake Guścierz Mały (Fig. 5). In this case, this is possible by maintaining a constant outflow character of the lake, with underground supply. However, due to the large alimentation area, the value of specific runoff is very small (q_{max} = 5.4 $l \cdot s^{-1} \cdot km^{-2}$, q = 2.7 $l \cdot s^{-1} \cdot km^{-2}$, q_{min} = 1.2 $l \cdot s^{-1} \cdot km^{-2}$).

Large draining and strongly draining lakes from group 2, also situated in watershed zones, react to changes in the catchment structure in a different way. In this case, the hydrological efficiency of lake catchments is proportional to their total areas. An increase in the proportion of passive areas does not reduce the outflow value (Fig. 6a, b). Thus, it could be assumed that these reservoirs are alimented both directly from active catchments (surface flow, initial river network) as well as indirectly by underground inflow of water from local catchments of areas without outflow. Moreover, a division of draining lakes into two categories conditioned by the morphometry of lake basins and their hydraulic relationships with underground water-bearing structures becomes visible. Generally, with an increase in depth of lakes their draining ability and consequently catchment efficiency increases. However, some lakes (Kamieniczno, Patulskie and Stężyckie) reveal a greater ability to accumulate underground inflow than the remaining reservoirs of this group (Fig. 6c). Such a situation should be attributed mainly to

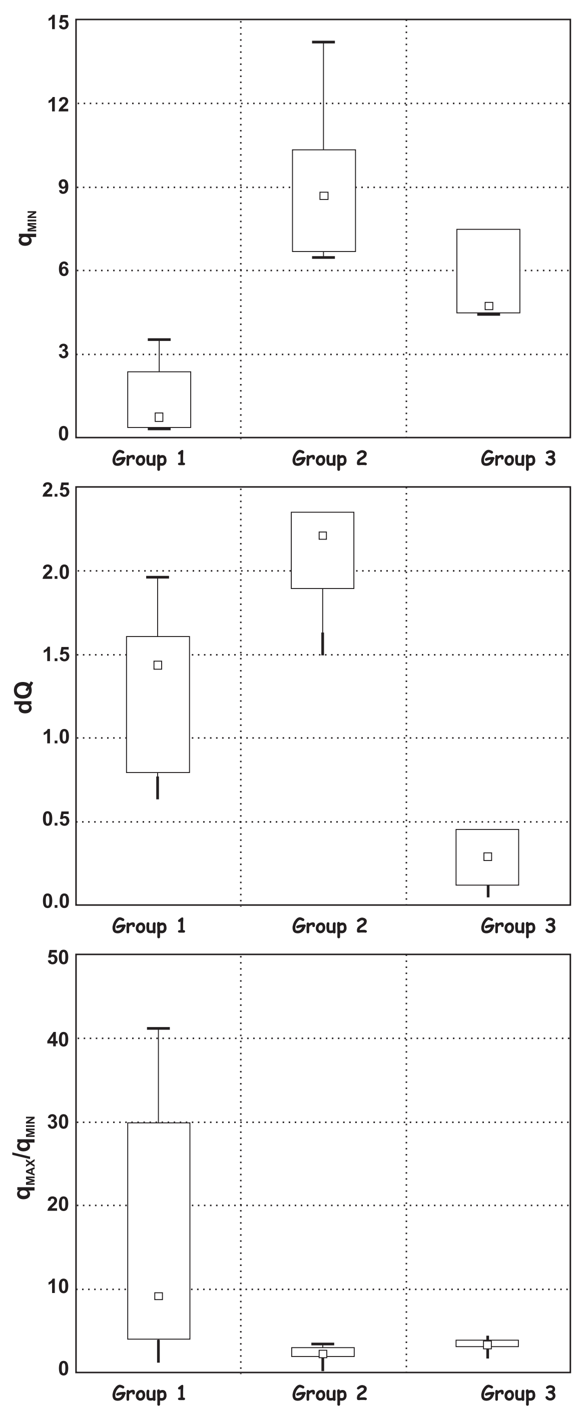

Fig. 4. Diversity of selected hydrological characteristics of lakes under study among groups

their favourable location with respect to underground routes of water flow rather than the possibility of draining deeper water-bearing horizons, whose outcrops are situated outside the topographic catchment.

The flow-through lakes of group 3 reveal an interesting property of decreasing relative values of underground inflow in the alimentation structure with an increase in the proportion of passive areas in the total catchment area (Fig. 7a). This can be explained by the fact that the main hydrographic objects trapping water excess accumulated within passive catchments are draining lakes situated in watershed zones. By collecting underground inflow, they transform it into surface outflow alimenting the flow-through lakes situated below. The higher seasonal variability of outflow from flow-through lakes can be explained by the reduction of the underground component with a simultaneous increase in the surface component of inflow (Fig. 7c). However the limited number of lakes in this group (Gowidlińskie, Jasień, Ostrzyckie) does not offer basis for further generalisations and can only reflect the impact of local conditions limited to the study area.

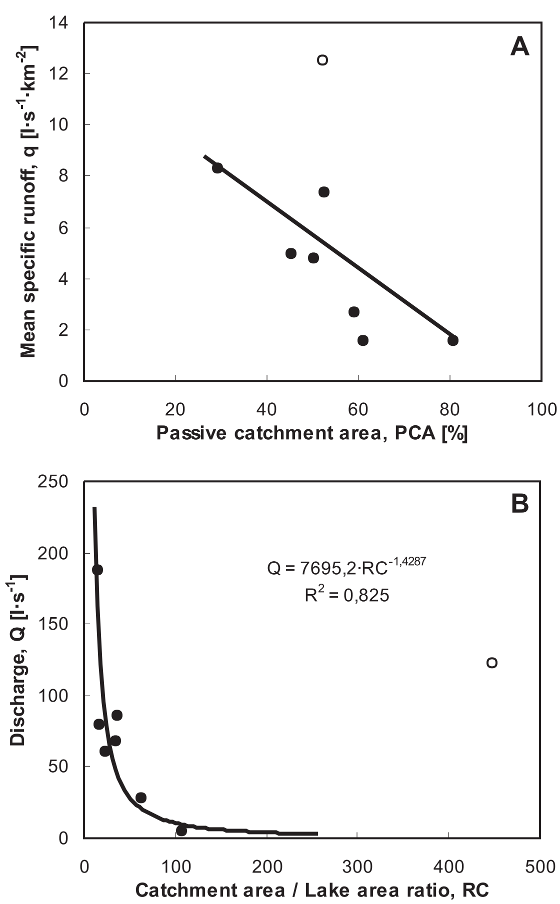

Fig. 5. Dependences between mean annual unit outflow and proportion of passive catchments (A) and between outflow from catchment and area of relative catchment in group of moderately draining lakes

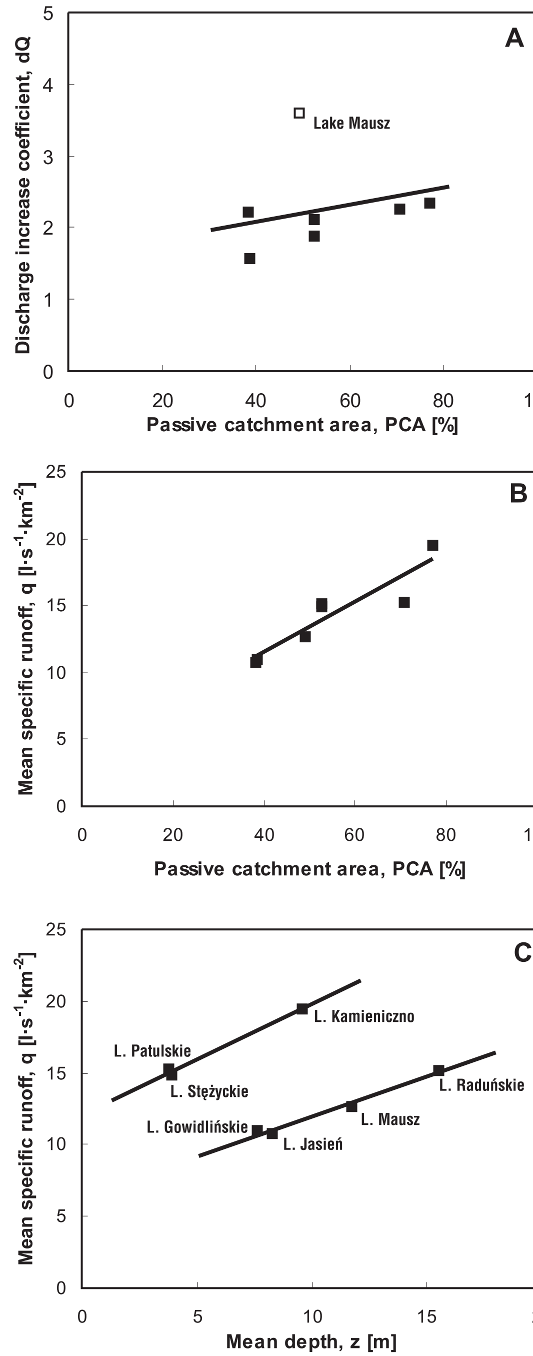

Fig. 6. Dependences between outflow increase ratio and proportion of area of passive catchment (A) , between mean annual unit outflow and proportion of passive catchment (B) and between unit outflow and mean depth of lakes (C) in group of draining and strongly draining lakes

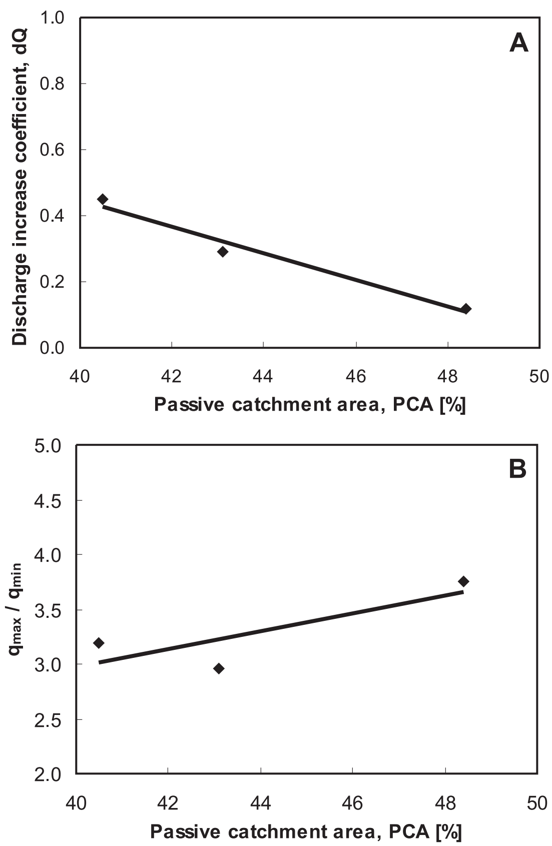

Fig. 7. Dependences between area of passive catchment and outflow increase ratio (A) and outflow irregularity ratio (B) in group of flow-through lakes

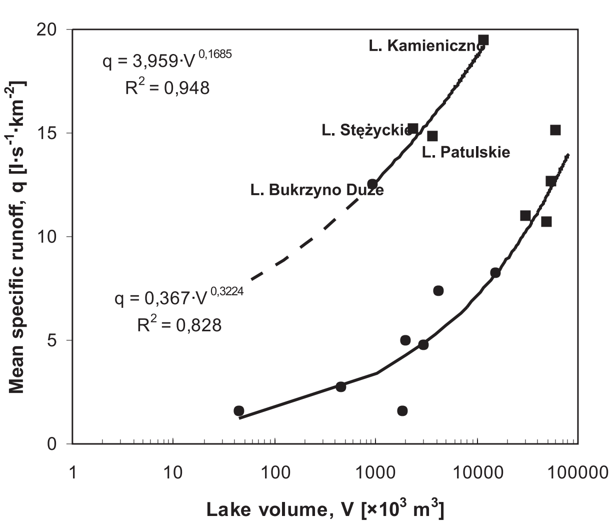

Fig. 8. Dependence between mean annual unit outflow and volume of moderately draining (circles) and draining and strongly draining lakes (squares)

Discussion

The performed survey of hydrological functions of flow-through lakes situated in the watershed zone of the Bytów and Kashubian Lakeland revealed the occurrence of at least three, clearly distinct, hydrological types of lakes, composed of: (1) strongly flow-through lakes, (2) moderately draining lakes and (3) draining and strongly draining lakes. The comparison of characteristics of outflow in each of the enumerated typological groups of reservoirs shows a close dependence of the characteristics of outflow from their catchments on the factors related to the structure of the catchment, especially relative relationships between the active and passive (without outflow) catchment. However, these influences assume various forms. In flow-through lakes (group 3) and moderately draining ones (group 1) changes in the percentage proportion of passive areas result in opposite changes of outflow, i.e. an increase in catchments without outflow is accompanied by a reduction in outflow, and vice versa, a decrease in the proportion of areas without outflow is favourable for an increase in the hydrological effectiveness of the catchment. In the case of draining lakes, this dependence does not occur, and the value of outflow is proportional to the area of total catchment. This confirms the fact that draining and strongly draining lakes are the main recipients of waters accumulated within areas without outflow, and, as was shown in earlier research (Borowiak & Barańczuk, 2005) the hydrological type of areas without outflow does not play any significant role here. It follows from the above that catchments without outflow are mainly the places of accumulation of deep circulation water, and not as was assumed by Drwal (1985) of far circulation. If this was the case, an increase in outflow in flow-through lakes would be visible, and this was not observed in the group of reservoirs under study. Actually, an opposite situation was observed, which proves that water from areas without outflow was already "trapped" by draining and strongly draining lakes, which in the cascade system are situated above flow-through lakes.

The factor limiting the hydrological efficiency of draining, strongly draining and flow-through lake catchments is, however, the size of the area covered by surface formations of lacustrine origin (gyttjas, clays, silts) and peatlands. The greater their proportion the smaller the hydrological efficiency of catchments. Thus, the outflow reduction is influenced by the area of these fragments of catchment without outflow that are covered by lacustrine gyttja, clay and silt sediments and peats rather than the total size of areas without outflow. This dependence does not concern moderately draining lakes, since (as it was mentioned above) catchments without outflow, especially evapotranspirative ones, where these formations usually occur, are not basically areas of their alimentation.

The draining capacity of reservoirs is conditioned both by morphometric features of lake basins as well as the system of local geological structures, determining the hydrological relationships of underground waters with lakes. Moderately draining lakes, situated in the balance diagram between draining and flow-through lakes (Fig. 2), are essentially similar to strongly draining lakes but their lower ability to accumulate underground inflow results from morphometric limitations (Fig. 8). Local geological conditions are, however, a factor of additional division within the draining lakes, both these moderately and strongly draining ones. Similar capacity of underground alimentation is revealed by Lake Stężyckie and Patulskie but also by much deeper and more capacious Upper Raduńskie. Local conditions also cause that Lake Bukrzyno Duże (in fact the group of lakes Bukrzyno Duże and Bukrzyno Małe), classified as moderately draining, is similar in terms of draining capacity to Lake Mausz and Jasień as well as Gowidlińskie due to high hydrological efficiency.

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Streszczenie

Wykorzystując ujęcie bilansowe przeprowadzono analizę związków pomiędzy funkcją hydrologiczną jezior a charakterystykami przyrodniczymi zlewni jeziornych i parametrami morfometrycznymi mis jeziornych. Jako wiodące przyjęto miary odnoszące się do struktury oraz zróżnicowania środowiska zlewni (względny udział zlewni aktywnej i pasywnej, zlewnia właściwa, utwory powierzchniowe, elementy struktury użytkowania gruntów).

Badaniami objęto 18 jezior położonych w górnych zlewniach rzek pomorskich (ryc. 1), grupujących jeziora o różnej hydrogenezie i morfometrii (tab. 1). Podstawą analizy były pomiary przepływu wykonane w latach 2004-2005 tworzące spójny materiał dokumentacyjny (ryc. 2). Stosując analizę skupień metodą Warda wydzielono trzy typy jezior: umiarkowanie drenujące, drenujące i silnie drenujące oraz przepływowe. Charakterystyki struktury bilansu wodnego oraz wybranych miar obiegu wody w zlewniach wydzielonych grup pokazano na rycinach 3-4. W małych jeziorach strefy wododziałowej (grupa 1) istnieją silne związki między powierzchnią zlewni czynnej i odpływem, a wzrost udziału obszarów pasywnych przyczynia się do jego zmniejszenia odpływu (ryc. 5a). Znamiennym jest, że z przyrostem zlewni właściwej odpływ jednostkowy nie zwiększa się (ryc. 5b), ponieważ wzrostowi powierzchni zlewni towarzyszy wzrost udziału powierzchni pasywnych. W jeziorach silnie drenujących (grupa 2) wydajność zlewni jest proporcjonalna do ich całkowitych powierzchni, a przyrost powierzchni obszarów pasywnych nie redukuje wielkości odpływu (ryc. 6a,b). Jeziora zasilane są zarówno ze zlewni aktywnych, jak i z lokalnych zlewni bezodpływowych. Część jezior ma większe możliwości akumulacji dopływu podziemnego dzięki dogodnemu usytuowaniu względem podziemnych szlaków przepływu wody (ryc. 6c). Przepływowe jeziora grupy 3. cechuje zmniejszanie się względnych wartości dopływu podziemnego w strukturze zasilania postępujące ze wzrostem udziału obszarów pasywnych w całkowitej powierzchni zlewni (ryc. 7a). Redukcją podziemnej i wzrostem powierzchniowej składowej dopływu należy tłumaczyć większą sezonową zmienność odpływu z tych jezior (ryc. 7b).

O możliwościach drenujących jezior decyduje zarówno morfometria mis jeziornych jak też układ lokalnych struktur geologicznych. Rola jezior umiarkowanie drenujących jest zbliżona do jezior silnie drenujących, a ich niższa zdolność akumulowania dopływu podziemnego wynika z ograniczeń morfometrycznych (ryc. 8). Lokalne warunki geologiczne są natomiast czynnikiem dodatkowego podziału jezior umiarkowanie i silnie drenujących.