Limnological Review 6 (2006): 31-38

Influence of hydrographic structure on outflow diversity in Upper Radunia catchment

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Abstract: On the basis of the survey of the hydrographic structure of the Upper Radunia catchment, units revealing various degrees of hydrological activity were distinguished within its area. It was observed that the diversity of hydrological efficiency of particular fragmentary catchments corresponds to the degree of organisation of river network, distribution of endorheic areas and the presence of large and deep lake basins alimented by deep circulation waters.

Key words: hydrographic structure of catchment, outflow, areas without outflow

Introduction

The upper Radunia catchment up to the profile in Goręczyno (210.5 km^2) constitutes 25.3% of the total area of the Radunia catchment. It is a fragment of the headwater area of the Kashubian Hydrographic System and represents in it the eastern direction of drainage. The drainage system of the upper Radunia embraces a group of 15 reservoirs forming a 48.1 km sequence of water bodies with just short interlake connections. This specific interrelation of lakes and streams in one coherent system of surface outflow justifies the term 'river-lake system'.

In terms of development and organisation the hydrographic network of the discussed catchment has features typical of areas of young Pleistocene post-glacial accumulation of South Baltic Lakelands. The initial character of the drainage system is manifested both in the poorly developed river network, using mainly bottoms of subglacial channels and former routes of melt waters outflow, and in the richness of elements of hydrographic network. The mean density of the permanent river network included in the general outflow system (without lake sections), expressed in Neumann's coefficient is 0.72 km·km^{-2}. Therefore the main form of surface waters in the catchment are reservoirs. Their role in water circulation is reflected in the lake density index of 12.4%, where the greatest proportion in the catchment area (10.6%) is taken by flow-through channel lakes included in the course of the Radunia. The main sequence includes lakes: Stężyckie, Upper and Lower Raduńskie, Kłodno, Małe and Wielkie Brodno, Ostrzyckie and Trzebno. The remaining reservoirs – Białe with Rekowo, Małe and Duże Bukrzyno and Lubowisko, Dąbrowskie and Patulskie are connected with the sequence by interlake connections to form one coherent draining system.

The initial character of the draining system is also reflected in the common occurrence of areas without outflow in the upper Radunia catchment. The percentage of areas not included in the general system of surface drainage, reaching 42.4%, is the highest in all the catchments within the Kashubian Hydrographic System.

As well as that, in the light of the research by Borowiak et al. (2000) this catchment reveals the greatest internal diversity of outflow values of all the headwater catchments in the Kashubian Hydrographic System (fig. 1). In the years 1980-1990 mean annual unit outflow had in particular fragmentary catchments very diverse values. The lowest unit outflow characterised the catchments of the Borucinka (4.9 dm^3·s^{-1}·km^{-2}) and Gołubska Struga with the system of Lakes Lubowisko – Dąbrowskie (5.3 dm^3·s^{-1}·km^{-2}).

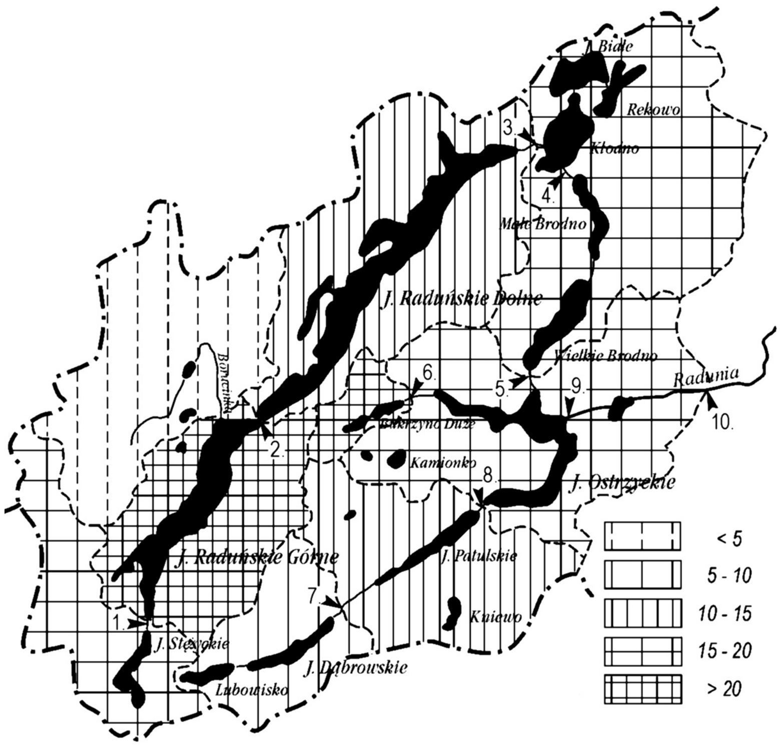

Fig. 1 Map of the specific discharge from the partial catchments of the upper Radunia River.

Discharge values ale given in $dm^3 \cdot s^{-1} \cdot km^{-2}$ (Borowiak et al. 2000). Designations of the discharge measurement sites: 1. – Stężyca, 2 – Borucino, 3 – Chmielonko, 4 – Zawory, 5 – Brodnica Dln., 6 – Czapielski Młyn, 7 – Gołubie, 8 – Krzeszna, 9 – Ostrzyce, 10 – Goręczyno

The most hydrologically efficient one was the direct catchment of the deepest reservoir of the area – Upper Lake Raduńskie (24.2 $dm^3 \cdot s^{-1} \cdot km^{-2}$). Unit outflows higher than the average for the whole catchment, which was 13.4 $dm^3 \cdot s^{-1} \cdot km^{-2}$, were observed in its eastern fragments with the sequence of lakes Rekowo – Białe –Kłodno – Brodno Małe – Brodno Wielkie – Ostrzyckie.

The aim of this paper is to analyse how the development and organisation of river network, mainly distribution of endorheic systems, influences the diversity of hydrological efficiency of particular fragmentary catchments within the upper Radunia catchment.

Methods

Since, apart from Goręczyno, there is no continuous multi-annual hydrometric control in the upper Radunia catchment, the spatial survey of outflow conditions from fragmentary catchments was performed on the basis of the results of systematic monthly hydrometric measurements preformed by the employees of the Department of Limnology of Gdańsk University in 2000-2004.

To determine the degree of development and organisation of the river-lake network, the method of network analysis was employed with the use of Horton-Strahler's classification. The cartographic basis for the calculated quantitative characteristics were topographic maps on 1:25 000 scale. The determination of the hydrographic structure of the catchment was also performed on the basis of topographic maps on 1:25 000 scale, and in especially doubtful places, on the basis of the analysis of maps on 1:10 000 scale and field mapping. In view of the previous studies on the relationships between the development and organisation of river network and outflow characteristics in the Kashubian Lakeland (Drwal 1982), as well as the hydrological activity in lake alimentation (Nowiński, Lange 2004), five basic types of hydrographic units were distinguished within the catchment. Hydrologically active units (A) include: lake-side areas (A_J), river-side areas of the Radunia and interlake connections (A_R), and catchments of permanent streams alimenting lakes (A_{III}). Passive units (P) include absorptive areas without outflow (P_C) and evapotranspirative areas without outflow (P_E). The role of water recipients in thus outlined hydrograpic structure is played by the Radunia and the reservoirs through which it flows: Lakes Białe and Rekowo, the Czapielska Struga with Bukrzyno Małe and Duże, oraz the Gołubska Struga with the system of Lakes Lubowisko – Dąbrowskie – Patulskie.

Results

The Radunia up to the closing profile in Goręczyno is a system of just IV order (Borowiak 2005). The river reaches the order after leaving Upper Lake Raduńskie, into which flows its largest tributary of III order – the Borucinka. From this point up to the closing profile, the Radunia receives three left-side tributaries (including the system of the Ręboszewska Struga, the second biggest one) and two right-side tributaries of III order, as well as numerous tributaries of lower orders. The analysis of the river-lake system of the upper Radunia showed that the Horton's law of the number of streams, whose measure is the bifurcation index R_B, is fulfilled. The mean bifurcation index for the whole drainage system here has a value of 5.94 and is comparable with the analysed by Bajkiewicz-Grabowska (2002) river-lake systems of north-eastern Poland. The system of the upper Radunia fulfils also another Horton's law – of mean stream length. The value of the index of mean stream length R_L is here 8.07 and is close to values characteristic of the systems of the Lithuanian Lakeland, which are at a stage of organisation (Bajkiewicz-Grabowska 2002).

The hydrographic structure of the upper Radunia catchment is presented in table 1. Lake-side areas cover 28.2% of the area, while river-side areas just 4.3%. The greatest percentage of lake-side areas is observed in Rekowo catchment (79.7%) and in the direct catchment of Lake Białe (61.3%), and the smallest in the direct catchment of Upper Lake Raduńskie (10.3%). In the most hydrologically active areas all the excess of water from atmospheric inflow is transported (continually or periodically) into lakes (lake-side areas) and the Radunia and interlake connections within the Raduńska-Ostrzycka channel (river-side areas). There is not only point inflow, via streams of I and II order, but also on the surface along the whole border with the recipient. In the study period these areas revealed substantial outflow diversity. In the periodically drained part the outflow index was 120-150 mm and increased in these fragments of lake-side and river-side areas which were continuously drained by I order streams (q – 5.7 $dm^3 \cdot s^{-1} \cdot km^{-2}$; H – 180 mm), and mainly these drained by II order streams (q – 11.5 $dm^3 \cdot s^{-1} \cdot km^{-2}$, H – 362 mm).

Table 1. Hydrographic structure of upper Radunia River catchment determined to main measurement sites
Designations: O – recipients, A_{III} – perennial third-oder catchment, A_R – near-river catchment, A_J – near-lake catchment, P_C – passive absortive catchment, P_E – passive evapotranspiration catchment

River	Outfall	Catchment structure in %					
		O	Active catchment			Passive catchment	
			A_{III}	A_R	A_J	P_C	P_E
Radunia	Stężyca	4.3	0.0	0.0	26.2	55.0	14.5
Radunia	Borucino	7.0	22.9	3.9	10.0	38.0	18.2
Radunia	Chmielonko	10.9	18.4	2.3	22.6	23.1	22.7
Radunia	Zawory	12.0	16.3	2.3	27.3	20.8	21.3
Radunia	Brodnica Dln.	11.3	19.5	2.5	25.8	18.5	22.4
Czapielska Struga	Czapielski Młyn	7.7	0.0	0.0	38.7	18.3	35.3
Gołubska Struga	Gołubie	8.9	0.0	5.7	29.2	25.8	30.4
Gołubska Struga	Krzeszna	6.7	0.0	7.4	31.8	14.9	39.2
Radunia	Ostrzyce	10.6	13.8	3.4	28.9	15.7	27.6
Radunia	Goręczyno	10.4	14.7	4.3	28.2	15.1	27.3

High activity was also observed in catchments of streams (of III order) alimenting lakes. These are areas in which a system of linear surface drainage functioning throughout the year developed, and the whole excess of water from the atmospheric inflow is discharged in the place of an outlet of a III order stream into the recipient. The value of unit outflow and outflow index from the Borucinka catchment, assumed to be representative of the Kashubian Lakeland (Drwal et al. 1975), in the years 2000-2004 were 3.96 $dm^3 \cdot s^{-1} \cdot km^{-2}$ and 124.9 mm respectively. Against the hydrological conditions of the Kashubian Lakeland these values are exceptionally low. However, if the active catchment (51.7% of topographic catchment) is taken as the reference area, unit outflow increases and is closer to average values for the whole Kashubian Lakeland – i.e. about 7.8 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (Cyberski, Dynus 1979). Moreover, the mentioned outflow values from the Borucinka catchment in 2000-2004 were by 19% lower than in 1980-1990 (Borowiak et al. 2000).

In the upper Radunia catchment the total area covered by III order catchments is 57.6 km². However, after deducting passive areas (whose proportion ranges from 14.6 to 58.2%), fragments of III order catchments included into the general outflow system constitute just 14.7% of the Radunia catchment. The area of an average III order catchment is 9.6 km², and of its active part 5.3 km². The largest one is the Borucinka catchment – 28.6 km², and the smallest – right-side tributary of Lake Brodno Wielkie – 2.8 km² (tab.2).

Table 2. Hydrographic structure of the third-order catchment

Designations: A_{III} – perennial third-oder catchment, P_C – passive absortive catchment, P_E – passive evapotranspiration catchment

River	Catchment of lake	Catchment area km²	Catchment structure in %		
			Active catchment	Passive catchment	
			A_{III}	P_C	P_E
Borucinka	Raduńskie Grn.	28.6	51.7	19.4	28.9
Łączyńska Struga	Raduńskie Dln.	6.2	56.3	3.7	40.0
Stream from Brodnica Grn.	Raduńskie Dln.	4.1	41.8	0.0	58.2
Ręboszewska Struga	Brodno Wielkie	12.2	58.1	12.7	29.3
Stream from Brodnica Dln.	Brodno Wielkie	2.8	55.8	0.0	44.2
Stream from Rokitki	Trzebno	3.7	85.4	0.0	14.6

Absorptive areas without outflow were treated as partially passive units, while evapotranspirative ones as totally passive. Absorptive areas without outflow are a category of hydrographic units usually related to permeable ground and that remain in hydrological coherence, basically limited to the underground phase, with open outflow systems. Their mean underground alimentation is estimated at about 280 mm (Drwal 1982). Absorptive areas without outflow, which cover 15.1% of the area of the upper Radunia catchment, are mainly located in its south-western part, and their proportion locally reaches 47% (Lake Lubowisko catchment) and 55% (Lake Stężyckie catchment).

Evapotranspirative areas without outflow are characterised by developed surface flow, and sometimes also developed local system of endorheic streams, radially directed towards centres of hollows. Water circulation in these areas occurs mainly through atmospheric exchange, and alimentation of waters of underground structures reaches values of about 90 mm (Drwal 1982). Areas of this type cover in total 27.3% of the area of the upper Radunia catchment. The largest (12.9 km²) compact evapotranspirative area without outflow is situated in the watershed zone between Upper Lake Raduńskie, the system of Ostrzyckie Lakes and system of Lakes Lubowisko – Dąbrowskie – Patulskie, as well as in the Borucinka catchment (8.2 km²) and in the direct catchment of Lake Patulskie (5.8 km²).

Discussion

The performed research confirms that the degree of organisation of the system of the upper Radunia influences the diversity of hydrological efficiency of individual hydrographic units within it (fig. 2.A.). The lowest outflow indices (from 16 to 118 mm) were observed in periodic streams (usually of I or II order) that occur at the highest morphological level of the Kashubian Lakeland (altitude 190-200 m a.s.l.). This group of streams usually consists of initial pluvial network which has a connection with the organised outflow system through young erosive cuts and anthropogenic ditches (Drwal 1982). They are alimented mainly by atmospheric precipitation and near-surface water-bearing horizon of local significance and variable efficiency during the year.

A slightly higher hydrological efficiency (from 59 to 119 mm) was observed in the main tributaries of the Radunia (including the Borucinka, Łączyńska Struga) that form systems developed on the basic plateau level (altitude 170-180 m) and draining subglacial channels. The deeper cutting of their valleys into the morphological level ensures alimentation throughout the year both from the near-surface and outwash levels, and (as in the case of the Borucinka) inflow of deep waters from intermorainic levels (Staszek 2003). An analogous alimentation manner is characteristic of the Gołubska Struga using the channel of Lakes Lubowisko-Dąbrowskie. The outflow from catchments of these lakes ranged from 130 to

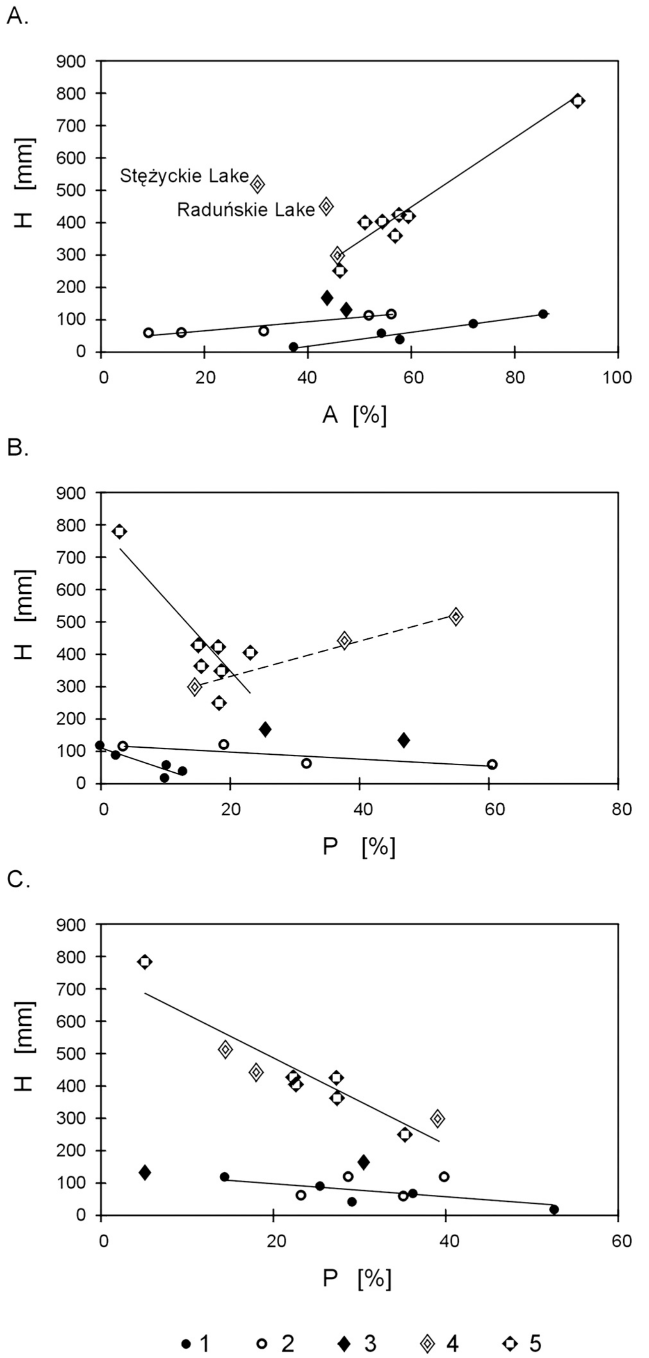

Fig. 2. Relationship between outflow index and percentage proportion of active catchment (A.), absorptive passive catchment (B.), evapotranspirative passive catchment (C.) in total catchment area.

Designations: A – active catchment, P_C – passive absortive catchment, P_E – passive evapotranspiration catchment, 1 – plateau streams, 2 – channel streams, 3 – Gołubska Struga, 4 – draining lakes, 5 – flow-through lakes

160 mm and was the lowest of all the channel lakes of the Raduńsko-Ostrzycka group.

The highest outflow indices, but also the most varying in values (from 367 from catchment of Lake Ostrzyckie to 786 mm from catchment of Lake Białe) were observed in catchments of lakes of the Raduńsko-Ostrzycka group, which are in the sequence of the Radunia flowing at the bottom of a subglacial channel at an altitude of about 160 m. The high value of outflow indices (on average 5 times higher than in streams of lower orders) confirms the draining role of lake basins with respect to all water-bearing horizons, i.e. near-surface, outwash, upper and lower intermorainic ones.

The performed research also indicates that the hydrographic structure of the catchment, and mainly the distribution of endorheic systems, influences the diversity of hydrological efficiency of individual hydrographic units. It was observed that an increase in proportion of passive catchment (both absorptive and evapotranspirative) in the total area of the catchment significantly contributes to a reduction of the outflow value (fig. 2.B., 2.C.). The character of this dependence, however, seems to be more complex in the case of absorptive passive catchments, which, according to Drwal (1982), are the main areas of alimentation of far circulation underground waters, and consequently of basic outflow that occurs at higher organisation levels of the Kashubian Hydrographic System.

The highest outflow reduction caused by an increased proportion of absorptive areas without outflow in the catchment structure is observed in reservoirs classified by Borowiak and Barańczuk (2005) as strongly flow-through ones (of outflow increase ratio dQ below 0.1), for which the basic source of water income , over 85%, is surface inflow. This group includes Lakes: Wielkie and Małe Brodno, Ostrzyckie and Trzebno. In the light of the obtained material, a change of the proportion of absorptive areas by 10% in the hydrographic structure causes reduction/increase of outflow from catchments of these lakes by about 200 mm (fig. 2.B.). In plateau streams alimented on the surface and near surface, these changes are about 65 mm, and the smallest (about 10 mm) are in channel streams alimented from deeper water-bearing horizons. The role assigned by Drwal (1982) to absorptive areas without outflow in the shaping of the outflow value from the catchment seems to become visible only in the case of such lakes as Stężyckie, Raduńskie or Patulskie, which belong to the strongest draining reservoirs of the Raduńsko-Ostrzycka group (with dQ > 0.75). The growing value (by 55 mm) of the outflow index from the catchments of these lakes, with the increase in proportion of passive absorptive catchments, is the reflection of both: the role of absorptive areas in the alimentation of far circulation underground waters, and the role of the underground component (over 50%) in the alimentation structure of these reservoirs. Moreover, relatively high (about 450-520 mm) values of this index from the catchments of lakes Stężyckie and Raduńskie result from the formation of underground outflow both within their catchments and in terrains outside their topographic boundaries. On the one hand this is inflow of local character (by outwash water-bearing horizon) from the catchment of Lake Lubowisko (Jankowska 1985), while on the other hand - interregional (by intermorainic levels) from the Wda catchment (Drwal 1982).

The increase in the proportion of evapotranspirative areas without outflow by 10% can cause outflow reduction both in lake catchments (on average by about 135 mm) as well as in lakeless catchments – on average by 20 mm (fig. 2.C.). It is, however, two times higher in flow-through lakes than in draining ones, and by almost 40% higher in plateau streams than streams flowing in subglacial channels.

The outflow organisation in catchments of Pomeranian lakes occurs only when there is an appropriately developed alimentation background, i.e. of catchment proper size 7.8. Only then is it possible to produce necessary excesses of water to form surface outflow (Lange 1986). From the dependences obtained for the upper Radunia catchment it follows that in order to form a surface outflow from flow-through lakes, the proportion of the active part in the hydrographic structure of their catchments cannot be lower than 19%, and the proportion of absorptive areas without outflow cannot be over 36% (fig. 2.A). In order to form outflow from plateau catchments, the minimum proportion of the active part cannot be lower than 31%, while the proportion of absorptive areas without outflow cannot be higher than 17%.

Conclusion

The upper Radunia catchment shows the furthest internal diversity of outflow values of all the headwater catchments within the Kashubian Hydrographic System. The research reveals that this is determined by the degree of organisation of river network, hydrographic structure of catchment (mainly the distribution of endorheic areas) as well as the presence of deep channel lakes alimented with deep circulation waters. The lowest outflow indices occur in periodical streams alimented mainly by atmospheric precipitation and near-surface water-bearing horizon of changing efficiency during the year. The highest outflow, confirming the draining role of lake basins with respect to all the IV order water-bearing horizons, was observed in the catchments of lakes of the Ostrzycko-Raduńska group within the sequence of the Radunia flowing at the bottom of a subglacial channel.

It was observed that the increase in the proportion of passive catchment (both absorptive and evapotranspirative) in the total area of catchment significantly contributes the reduction of outflow value. The highest outflow reduction is observed in strongly flow-through reservoirs in which the main source of water income (>85%) is surface inflow. The reduction is much less clear in streams alimented from deeper water-bearing horizons. On the other hand, the fact of growing, with the increase in the proportion of absorptive areas without outflow, value of outflow index from catchments of strongly draining lakes, reflects both the role of absorptive areas in the alimentation of far circulation underground waters as well as of the underground component (over 50%) in the structure of alimentation of these reservoirs.

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Streszczenie

Dorzecze górnej Raduni wykazuje najdalej posunięte wewnętrzne zróżnicowanie miar odpływu ze wszystkich zlewni źródliskowych wchodzących w skład kaszubskiego systemu hydrograficznego (ryc.1).

Na podstawie przestrzennego rozpoznania warunków odpływu ze zlewni cząstkowych dokonanego w oparciu o wyniki patrolowych pomiarów hydrometrycznych wykonywanych w latach 2000-2004 oraz analizę struktury hydrograficznej zlewni (tab.1, 2), dokonano oceny wpływu wykształcenia i organizacji sieci rzecznej na zróżnicowanie wydajności hydrologicznej rozpatrywanych jednostek hydrograficznych.

Stwierdzono, iż najniższymi wskaźnikami odpływu (od 16 do 118 mm) charakteryzowały się cieki okresowe (przeważnie I i II rzędu) zasilane głównie przez opady atmosferyczne i przypowierzchniowy poziom wodonośny o zmiennej w ciągu roku wydajności (ryc. 2.A.). Większą wydajność hydrologiczną (od 59 do 119 mm) wykazywały główne dopływy Raduni odwadniające rynny subglacjalne i zasilanie w ciągu całego roku zarówno z poziomu przypowierzchniowego jak też sandrowego, a miejscami również z ascenzyjnego dopływu wód wgłębnych z poziomów międzymorenowych. Najwyższe odpływy (od 254 do 786 mm) obserwowano ze zlewni jezior grupy raduńsko-ostrzyckiej znajdujących się w ciągu Raduni płynącej w dnie rynny subglacjalnej na poziomie około 160 m n.p.m. Wysoka wartość wskaźników odpływu potwierdza drenującą rolę niecek jeziornych w stosunku do wszystkich czwartorzędowych poziomów wodonośnych.

Stwierdzono, że wzrost/spadek udziału zlewni pasywnej (zarówno chłonnej, jak i ewapotranspiracyjnej) w powierzchni całkowitej zlewni zasadniczo przyczynia się do redukcji/przyrostu wielkości odpływu (ryc. 2.B., 2.C.). Największych zmian wielkości należy oczekiwać w zbiornikach silnie przepływowych, dla których podstawowym źródłem przychodów wody (>85%) jest dopływ powierzchniowy. Mniej wyraźne zmiany zachodzą w ciekach zasilanych z głębszych poziomów wodonośnych. Z kolei rosnąca wraz ze wzrostem udziału zlewni pasywnych chłonnych wartość wskaźnika odpływu ze zlewni zbiorników silnie drenujących jest odzwierciedleniem zarówno roli obszarów chłonnych w alimentacji wód podziemnych dalekiego krążenia, jak i roli składowej podziemnej (przekraczającej 50%) w strukturze zasilania tych zbiorników.

Z uzyskanych dla zlewni górnej Raduni zależności wynika, że aby możliwe było sformowanie odpływu powierzchniowego z jezior przepływowych udział części aktywnej w strukturze hydrograficznej ich zlewni nie może być niższy od 19%, zaś udział obszarów bezodpływowych chłonnych nie może przekraczać 36%.