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THE ROLE OF LAKES IN NATURAL GROUNDWATER DRAINAGE

Abstract: In the paper it is shown that the lakes of the North-Eastern Poland fulfil various functions in the groundwater phase of the water circulation. The value of the resultant of the groundwater supply to the lake, and in some cases also its direction, depend on the volume of the water undergoing a total exchange in the reservoir in the given year. In through-flow lakes the runoff increase coefficient also influences this value.

Keywords: lake, water balance of a lake, groundwater drainage.

1. INTRODUCTION

Lakes not only level off the runoff from the rivers flowing through them, but they also influence the amount of the river runoff, causing its increase or decrease. This fact is related to the draining role of the lake bowls, which may drain various aquifers. While a river flowing through lakes drains only the subsurface aquifer, lakes – in particular ribbon lakes, because of their depth – are in hydraulic contact with deeper water, whose aquifers are often situated on the routes of the "remote" transit groundwater circulation. Lakes can drain water from such aquifers, which increases river runoff, or they can also supply water to them, which decreases water supply to rivers.

The fluctuations of the water table in a lake can affect the exclusion from the river runoff of water from the deeper aquifers or its inclusion in it. Which of the above happens is determined by the systems of hydrostatic pressure head formed in the lake bowl and in aquifers connected with them.

The drainage of aquifers depends on the system "lake bowl – aquifer". The first aquifer, which has a direct hydraulic contact with the lake, feeds it due to the lowering of the water table. Deep aquifers, cut by the lake basin, supply water to the lake due to the difference in the pressure head (groundwater tables are under the subartesian or artesian piezometric pressure). Supply from the deep, confined aquifers can happen through the sources situated at the bottom of the bowl, or else by means of slow capillary ascension (Nowakowski et al., 1996).

The hydrogeological condition in some lakelands (e.g., Suwałki Lakeland) may cause a mutually limited lateral hydraulic contract of aquifers.

Of fundamental importance here are vertical hydraulic connections manifested in the cascade character of the piezometric surface. Due to the domination of the vertical hydraulic contact over the lateral one, the shape of the piezometric surface (pretends) mimics the course of the bottom-most layers of an aquifer. The drainage of confined groundwater in the region in question occurs only locally and even very deep lakes do not participate in it. The supply of water to a hydrographical network takes place not only through the surface runoff, but also through the drainage of unconfined groundwater perched with respect to confined groundwater in the whole region of the plateau and strongly isolated from it even in the regions of topographical depressions (Mitręga, 1988; Mitręga, Paczyński, 1982).

That the connections between lakes and groundwater depend on the local geological structure is confirmed by the research Lithuanian (Barisas et al., 1987, 1998). According to them supply of groundwater to lakes located in the watershed zone within terminal moraines is usually weak; in the groundwater exchange in lakes situated in such regions loss of water may dominate sometimes, due to the seeping to groundwater through the bottoms of the lake bowls. Those lakes, however, which are situated at the lithological contacts of sandy wash-plains on the distal slopes of the moraine sequence are particularly rich in groundwater seeping below the water table.

From many studies conducted in lakelands it follows that the underground feeding supply of lakes, in particular of ribbon lakes, is very large, and the natural drainage comes both from shallow and deep aquifers, of which there can be many. Studies of water balance of lakes in Northern Poland show that the share of the groundwater in to a lake feeding may constitute from a few to several tens percent of the balance total (Bajkiewicz-Grabowska, 1985; Okulanis, 1985; Borowiak, 2000).

2. THE RESEARCH METHOD

The components of the groundwater phase of the water circulation in a lake are among the basic features of the groundwater resources of the zone of their active exchange with surface water. They can be determined by various methods, for instance by solving the detailed equation of the water balance of a reservoir, taking into account (whenever possible) all the input and output components of the water balance (Bajkiewicz-Grabowska, 1985). This equation can be represented as

$$(P_j - E_j) + (\Sigma D_j - H_j) + \Delta Z_{gw} = \Delta R_j$$

where: P_j, E_j, H_j, ΔR_j – as above, ΣD_j – the sum of the river and uncontrolled inflows from the direct catchment area of the lake, ΔZ_{gw} – the resultant of the lake feeding by the groundwater.

Underground exchange is the resultant of the lake feeding by the groundwater. It is the difference between the sum of the groundwater inflow to the

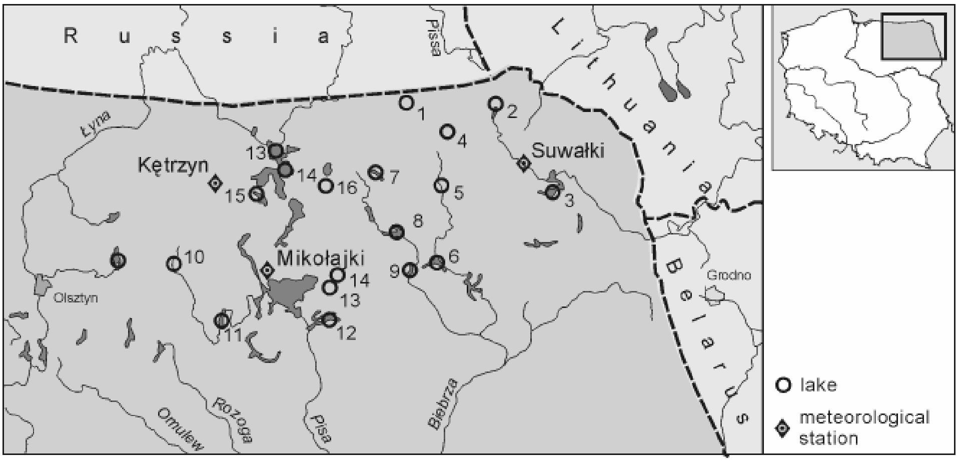

Fig. 1. Location of selected lakes. Lakes: 1 – Gołdap, 2 – Hańcza, 3 – Wigry, 4 – Rospuda, 5 – Olecko Wielkie, 6 – Selmęt Wielki, 7 – Litygajno, 8 – Łaśmiady, 9 – Ełckie, 10 – Gielądzkie, 11 – Mokre, 12 – Roś, 13 – Orzysz, 14 – Druglin, 15 – Dejguny, 16 – Szóstak.

lake and the groundwater runoff. It is determined from the balance difference as

$$\Delta Z_{gw} = [(P_j - E_j) + (\Sigma D_j - H_j)] + \Delta R_j$$

A positive value of ΔZ_{gw} indicates the domination of the groundwater inflow to the lake, which means that the lake drains the aquifers. A negative value of ΔZ_{gw} means that the groundwater phase of the water circulation is dominated by the runoff, thus the lake water accrets the aquifers.

The available hydrometric material, fairly homogenous and allowing for an independent estimate of the balance elements was used to create water balance statistics of 16 lakes in North-Eastern Poland (Fig. 1). The balance covered the years 1971–1990. One month was accepted as the basic balance period; the quantitative characteristics of the water circulation in the hydrological years have been calculated by adding up the monthly values.

3. RESULTS AND CONCLUSIONS OBTAINED

Detailed water balances of the lakes in the North-Eastern Poland have shown that reservoirs fulfil various functions in the groundwater phase of the water circulation.

One group consists of lakes, where the yearly resultant of the underground feeding in the entire multi-annual period under investigation was always positive. This means that in each year underground feeding of the lake was the dominating component. Therefore, such lakes drain the aquifers with which they have a hydraulic contact. Lakes from this group increase the river

Table 1.

Groundwater inflow to the lakes draining the aquifers (1971 – 1990)

Lake	Groundwater inflow to the lake calculated:							
	using water balance				using total runoff			
	mean annual		maximal annual		minimal annual		mean annual	
	mln m^3	$m^3 \cdot s^{-1}$	mln m^3	$m^3 \cdot s^{-1}$	mln m^3	$m^3 \cdot s^{-1}$	$m^3 \cdot s^{-1}$	mln m^3
Olecko Wielkie	3,620	0,115	7,993	0,253	1,037	0,033	0,060	1,896
Rospuda	2,689	0,085	3,309	0,105	2,045	0,065	0,085	2,689
Gołdap	12,130	0,385	29,735	0,943	6,188	0,196	0,491	15,469
Wigry	33,224	1,054	63,228	2,005	17,499	0,555	1,155	36,434
Orzysz	21,208	0,672	64,115	2,033	0,150	0,005	0,566	17,834

Table 2.

Supply to the aquifers by the infiltrating lakes (1971 – 1990)

Lake	Groundwater inflow to the lake calculated:							
	using water balance				using total runoff			
	mean annual		maximal annual		minimal annual		mean annual	
	mln m^3	$m^3 \cdot s^{-1}$	mln m^3	$m^3 \cdot s^{-1}$	mln m^3	$m^3 \cdot s^{-1}$	$m^3 \cdot s^{-1}$	mln m^3
Litygajno	15,418	0,488	49,062	1,556	3,099	0,098	0,298	9,407
Łaśmiady	16,932	0,537	54,934	1,742	4,672	0,148	0,566	17,857
Ełckie	7,630	0,242	22,587	0,716	3,228	0,102	0,134	4,212
Selmęt Wielki	12,646	0,401	65,760	2,085	3,101	0,098	0,134	4,212

runoff, because they cause the inclusion of water obtained from the groundwater drainage in the runoff. Therefore, the groundwater runoff component in the total river runoff flowing out of such lake is increased by the water volume that the reservoir obtains through groundwater. Examples of such lakes are: Olecko Wielkie, Rospuda, Gołdap and Wigry[1]. Lake Orzysz also belongs to this group, although in the multi-annual period under investigation (1981 – 1982) this lake recharged the groundwater (Table 1).

Another group consists of reservoirs, where groundwater runoff dominates in the groundwater phase of the water circulation. In general, in each year

[1] Since 1989 a clear tendency to decrease the groundwater inflow to Lake Wigry has been occurring. In 1990, the recharge of groundwater from the lake was 4.258 millions cubic metres.

Table 3.

Components of the underground exchange in the lakes with variable function of the natural groundwater drainage

Lake	Groundwater inflow to the lake calculated:							
	using water balance				using total runoff			
	groundwater inflow to the lake		groundwater runoff from the lake		resultant of the groundwater supply		ground-water supply	ground-water runoff
	mln m^3	$m^3 \cdot s^{-1}$	mln m^3	$m^3 \cdot s^{-1}$	mln m^3	$m^3 \cdot s^{-1}$	$m^3 \cdot s^{-1}$	mln m^3
Dejguny	1,302	0,041	1,188	0,038	0,114	0,004	0,008	0,252
Szóstak	1,146	0,036	1,041	0,033	0,105	0,003	0,024	0,757
Mokre	2,010	0,064	1,109	0,035	0,901	0,029	0,653	20,593
Roś	55,252	1,752	0,374	0,012	54,878	1,740	1,791	56,481
Druglin	0,788	0,025	0,821	0,026	-0,043	0,001	n.d.	
Gielądzkie	1,195	0,038	1,396	0,044	-0,201	0,006	0,161	5,077
Hańcza	0,754	0,024	0,937	0,300	-0,183	0,006	0,017	0,536

of the multi-annual period under investigation the resultant of feeding by the groundwater was negative. These are therefore reservoirs recharging the groundwater. Since they direct some of the water to the aquifers, such lakes cause the decrease of the runoff of the rivers flowing out of them, and the groundwater runoff component in the total runoff of such river does not increase.

The lakes Litygajno, Łaśmiady and Ełckie, drained by the Ełk River as well as Lake Selmęt Wielki, drained by the Lega River constitute reservoirs recharging the aquifers (Table 2). These lakes, together with the rivers flowing through them, are situated in the vast valleys of the fluvioglacial runoff.

The next group is formed by lakes whose function in the groundwater phase of the water circulation is variable: once they drain the groundwater, once they recharge it. The resultant of the underground feeding of these lakes measured during each year of the period under investigation is sometimes negative and sometimes positive: depending on the year, groundwater inflow to the lake or groundwater runoff dominates. Such lakes either increase the groundwater runoff component of the total runoff from the lake, or else they decrease the river runoff, directing some of water to the aquifers. Two subgroups can be distinguished here: one of them consists of reservoirs in which in the groundwater phase of the water circulation in the years 1971 – 1990 drainage dominated; the other one, of those lakes in which in the same period infiltration dominated. In the first subgroup are: Lakes Dejguny, Szóstak, Mokre and Roś; in the second one, Lakes Druglin, Gielądzkie and Hańcza (Table 3).

Of particular importance is the groundwater exchange in Lake Hańcza. The water exchange of this lake, the deepest in Poland and whose bowl is over 100 metres deep and cuts apart the Quaternary deposits, is barely 0.183 cubic hectometres per year. The role of this lake in the groundwater drainage is comparable with that of the much shallower lakes Druglin and Gielądzkie. One does not observe an intensive exchange or a large share of the confined groundwater in feeding of this lake; this can be explained by the existence of barriers and hidden drainage zones along the groundwater flow (Mitręga et al., 1993). The circulation of groundwater and its hydraulic connection with the entire hydrographical network in the Suwałki Lakeland follows necessarily from the structure of the Quaternary bedding. The ribbon lakes of this lakeland (a. o. Lakes Hańcza, Szelment Wielki, Szelment Mały) show, contrary to the prevalent opinion, a limited hydraulic contact with the groundwater surrounding them (Mitręga et al., 1993). For the shallow unconfined aquifer Lake Hańcza is a drainage zone, but at the same time the water table of this lake lies around 1 m above the piezometric surface, which creates favourable conditions for the infiltration of the lake water to the aquifer. In practice, there is no hydraulic contact of the lake water with the deeper aquifers whose water flows around the lake basin (Mitręga, Pachla, 1984).

Water balances of the lakes under investigation allow for the verification of the existing views about the role of these hydrographical objects in the natural groundwater drainage.

In the literature of the subject it is accepted that the amount of the groundwater inflow to a lake depends on the size of the reservoir and the depth of its bowl: the larger and deeper the reservoir, the better its capabilities for the groundwater drainage, thus the inflow of groundwater to the reservoir is greater.

Calculations of the water balance of lakes have shown that the volume of water participating in the underground exchange does not depend on the depth of the reservoir. An evidence for that is, for example, Lake Hańcza, which despite of its being the deepest lake participates only to a small degree in the groundwater phase of the water circulation.

The depth of the lake basin may, in some cases, affect the direction of the underground exchange between the drainage area and the lake. If the lake is so deep that it has hydraulic contact with confined aquifers and the hydraulic pressure head in these aquifers is sufficient to make their recharge possible, then the depth of the lake may indicate the infiltrational character of the reservoir.

Water balances of lakes have shown that the value of the resultant of the lake feeding by the groundwater, and in some lakes also its direction (inflow or outflow), depend on the volume of the water undergoing a complete exchange in the lake during the given year, that is, on the balance sum. The more lake water in a given year is in circulation, the greater the resultant of the feeding by the groundwater the lake.

Table 4.

Dependence on the resultant of the lake feeding by the groundwater (ΔZ_{gw}) on the water volume subject to annual exchange in the lake (SB)

Lake		Regression function ($y = \Delta Z_{gw}$; x = SB)	Determination coefficient (R^2; $p < 0,05$)
Draining	Olecko Wielkie	$y = -0,0011x^2 + 0,2989x - 1,1630$	0,9825
	Rospuda	$y = -0,0564x^2 + 1,2289x - 3,7684$	0,3959
	Gołdap	$y = 0,0073x^2 - 0,8744x + 35,011$	0,5604
	Wigry	too weak to be described	
	Orzysz	$y = -0,0106x^2 + 0,8007x + 24,877$	0,5717
Infiltrating	Litygajno	$y = -0,0017x^2 - 0,0715x + 7,2013$	0,6498
	Łaśmiady	$y = 0,0008x^2 - 0,5055x + 54,156$	0,4267
	Ełckie	too weak to be described	
	Selmęt Wielki	too weak to be described	
Draining-infiltrating, $\Delta Z_{gw} > 0$	Dejguny	$y = -0,0232x^2 + 0,7455x - 5,0717$	0,6919
	Szóstak	too weak to be described	
	Mokre	$y = -0,0017x^2 + 0,3741x - 16,784$	0,3363
	Roś	$y = -0,0008x^2 + 0,5694x + 60,54$	0,7661
Draining-infiltrating, $\Delta Z_{gw} < 0$	Druglin	too weak to be described	
	Gielądzkie	too weak to be described	
	Hańcza	$y = -0,0274x^2 + 0,5665x - 2,9108$	0,2407

If the lake in question drains the aquifers then the lake feeding by the groundwater increases together with the increase of the balance sum (Table 4). This increase is either limited only by the volume of water undergoing a complete exchange in the lake (e.g., Lake Olecko Wielkie), or else it is limited up to a certain level, above which the groundwater inflow to the lake is constant and does not depend anymore on the balance sum (e.g. Lake Rospuda); or else, the increase of the groundwater inflow to the lake starts only after a certain volume of water, critical for the given reservoir and subject to the yearly exchange is exceeded (e.g., Lake Gołdap).

A different behaviour is exhibited by Lake Orzysz. The volume of water participating in the exchange during a year determines the hydrological function of this lake. The critical value for this lake is equal to around 86 millions cubic metres of water. The smaller the balance sum with respect to this limiting volume, the more groundwater flows into the lake, while the greater the balance sum, the greater the groundwater runoff from the lake.

In the lakes which accret groundwater the increase of the balance sum causes the increase of the groundwater runoff from the lake, and hence an increased accretion of the groundwater (Table 4). Nonetheless, when too small volume of water circulates in a lake (e.g., Lake Litygajno: below 69 million

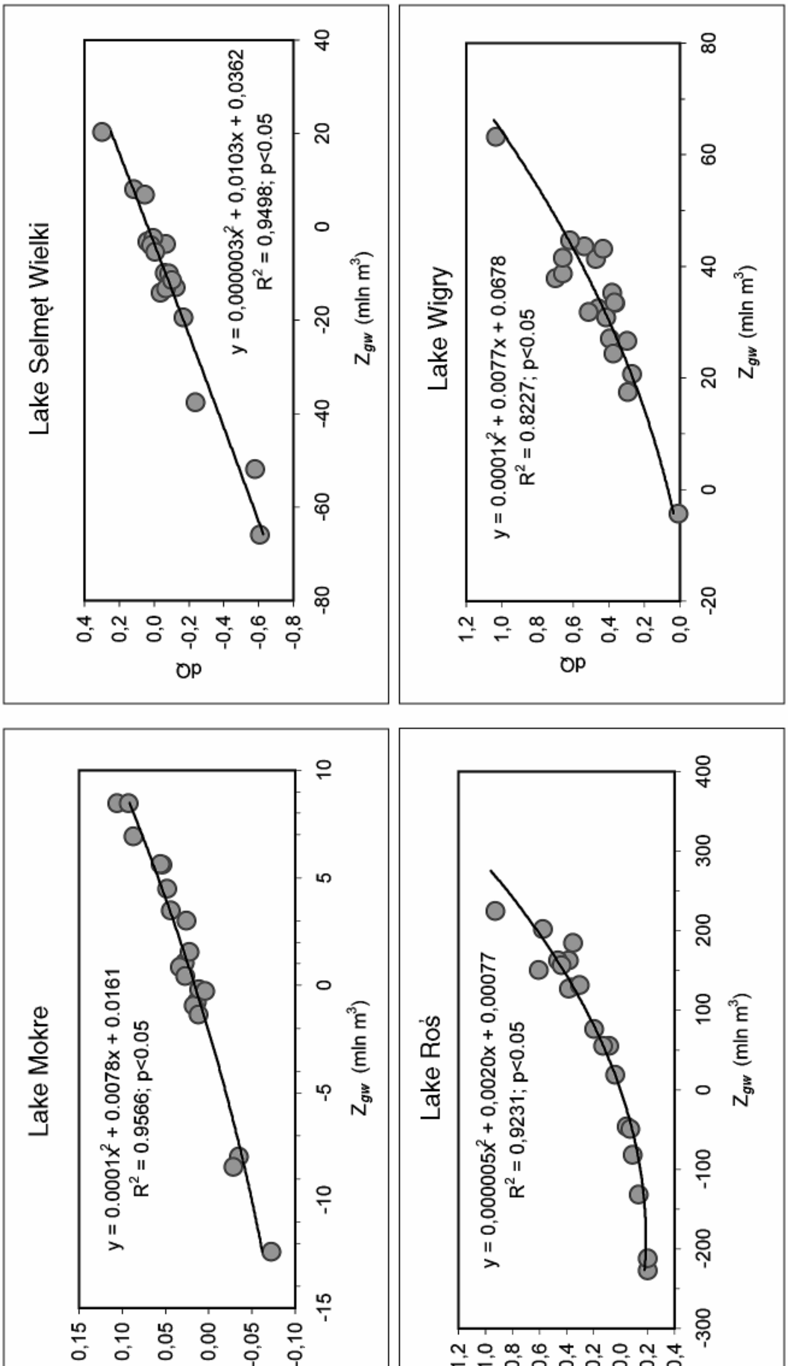

Fig. 2. Dependence of the runoff increase coefficient (dQ) on the resultant of the lake feeding by the groundwater (examples).

Table 5.
Dependence of the runoff increase coefficient (dQ) upon the resultant of the lake feeding by the groundwater, in million cubic metres (ΔZ_{gw})

Lake	Regression function (y = dQ; $x = \Delta Z_{gw}$)	Determination coefficient (R^2; $p < 0{,}05$)
Orzysz	$y = 0{,}0022x^2 + 0{,}0234x - 0{,}714$	0,8731
Roś	$y = 0{,}000005x^2 + 0{,}0020x + 0{,}00077$	0,9231
Mokre	$y = 0{,}0001x^2 + 0{,}0078x + 0{,}0161$	0,9566
Litygajno	$y = 0{,}0002x^2 + 0{,}0171x + 0{,}0257$	0,9017
Łaśmiady	$y = 0{,}000029x^2 + 0{,}00534x + 0{,}0105$	0,8583
Ełckie	$y = - 0{,}000057x^2 + 0{,}004x + 0{,}0063$	0,8965
Selmęt Wielki	$y = 0{,}000003x^2 + 0{,}0103x + 0{,}0362$	0,9498
Gołdap	$y = 0{,}0003x^2 + 0{,}0044x + 0{,}097$	0,9095
Wigry	$y = 0{,}0001x^2 + 0{,}0077x + 0{,}0678$	0,8227

cubic metres; Lake Łaśmiady: below 163 million cubic metres), the function of the reservoir changes from infiltrating to draining. In such cases the smaller the balance sum the larger the groundwater flow into the lake.

In a group of lakes with varying function of the natural groundwater drainage, when the volume of water undergoing the yearly exchange in the lake decreases, the role of such reservoir in the drainage increases (the groundwater flow to the lake increases), while when the balance sum increases, the draining role of the lake increases (the groundwater runoff increases) (Table 4).

An analysis of balance data has shown that the lake feeding by the groundwater depends also on the so-called runoff increase coefficient (dQ)[2], which reflects the relations between the horizontal and the vertical water exchange in the lake. The dependence of the runoff increase coefficient on the resultant of the lake feeding is shown in Table 5 and Fig. 2.

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[2] The runoff increase coefficient (dQ) is the quotient of the difference between the mean annual river runoff of the river flowing out of the lake (Q_w) and the mean annual runoff of the watercourses supplying water to the lake (Q_d) to the mean annual runoff of the watercourses suppying water to the lake (Q_d); $dQ = (Q_w - Q_d) / Q_d$ (Borowiak, 2000).

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