

## EFFECT OF THE LAKE LOCATION WITHIN THE TERRITORIAL HYDROGRAPHIC SYSTEM ON THE WATER CONDUCTIVITY

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### Abstract

Conditions of the water cycle and the structure of supply of lakes with water are dependent on location within the spatial hydrographic systems and linear river-lake systems. The position of the lake in the system determines the proportions between the surface and underground water supply and the ability of water bodies to increase drainage. On the basis of the studies carried out in the catchment area of the upper Radunia (Kashubian Lake District) in the years 2000-2010 it was found that short, often periodic watercourses usually have a low specific conductivity of about  $100 \mu\text{S}\cdot\text{cm}^{-1}$ . With the increasing development of the hydrographic network and the greater participation of water supply from deeper aquifers the mineralisation of water in streams also increases and the conductivity values periodically reach approx.  $400 \mu\text{S}\cdot\text{cm}^{-1}$ . The conductivity of the lakes of the upper Radunia is generally lower than that of the water of the watercourses, which is due to the ability of lakes to transform matter. The conductivity values of the surface water of lakes range from approx.  $70 \mu\text{S}\cdot\text{cm}^{-1}$  (Zamkowisko) to  $362 \mu\text{S}\cdot\text{cm}^{-1}$  (Bukrzyno Małe), while the average for all the described lakes is  $259 \mu\text{S}\cdot\text{cm}^{-1}$ . The recognised correlation indicates that the balance between different forms of water supply affect the chemical composition of the water and its total mineralisation. The supply of groundwater depends on, among others, the predisposition of the basin to drain aquifers as well as its location in a hierarchically organised hydrographic system. It is noticeable also that shallow lakes (mostly in local catchments) show the greatest diversity of conductivity - from  $158 \mu\text{S}\cdot\text{cm}^{-1}$  (Szewinko) to  $362 \mu\text{S}\cdot\text{cm}^{-1}$  (Bukrzyno Małe). Lakes of this type show a clear predominance of one type of water supply (e.g. surface water supply in Lake Szewinko, river water supply in Glinno and underground water supply in Bukrzyno Małe), which determines water mineralisation. The conductivity of the water of the medium-depth lakes ( $H_{\text{max}}$  5-10 m) in the headwaters catchment does not show a large variation; it is within the range of  $250\text{-}300 \mu\text{S}\cdot\text{cm}^{-1}$ . Lake Lubowisko in the local catchment has a lower conductivity ( $202 \mu\text{S}\cdot\text{cm}^{-1}$ ), which is caused by a higher significance of precipitation in the structure of its water supply. This is similar in the case of deep lakes in the elementary catchment. Lake Zamkowisko is supplied mainly through precipitation and the conductivity of its water is only  $70 \mu\text{S}\cdot\text{cm}^{-1}$ . The water of the deep and very deep lakes, in the headwater catchments and river basins, do not show a large variation of conductivity, but this value is also dependent on the participation of different sources of water in the lakes.

**Keywords:** river-lake system, hierarchical hydrographic system, water conductivity

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## 1. INTRODUCTION

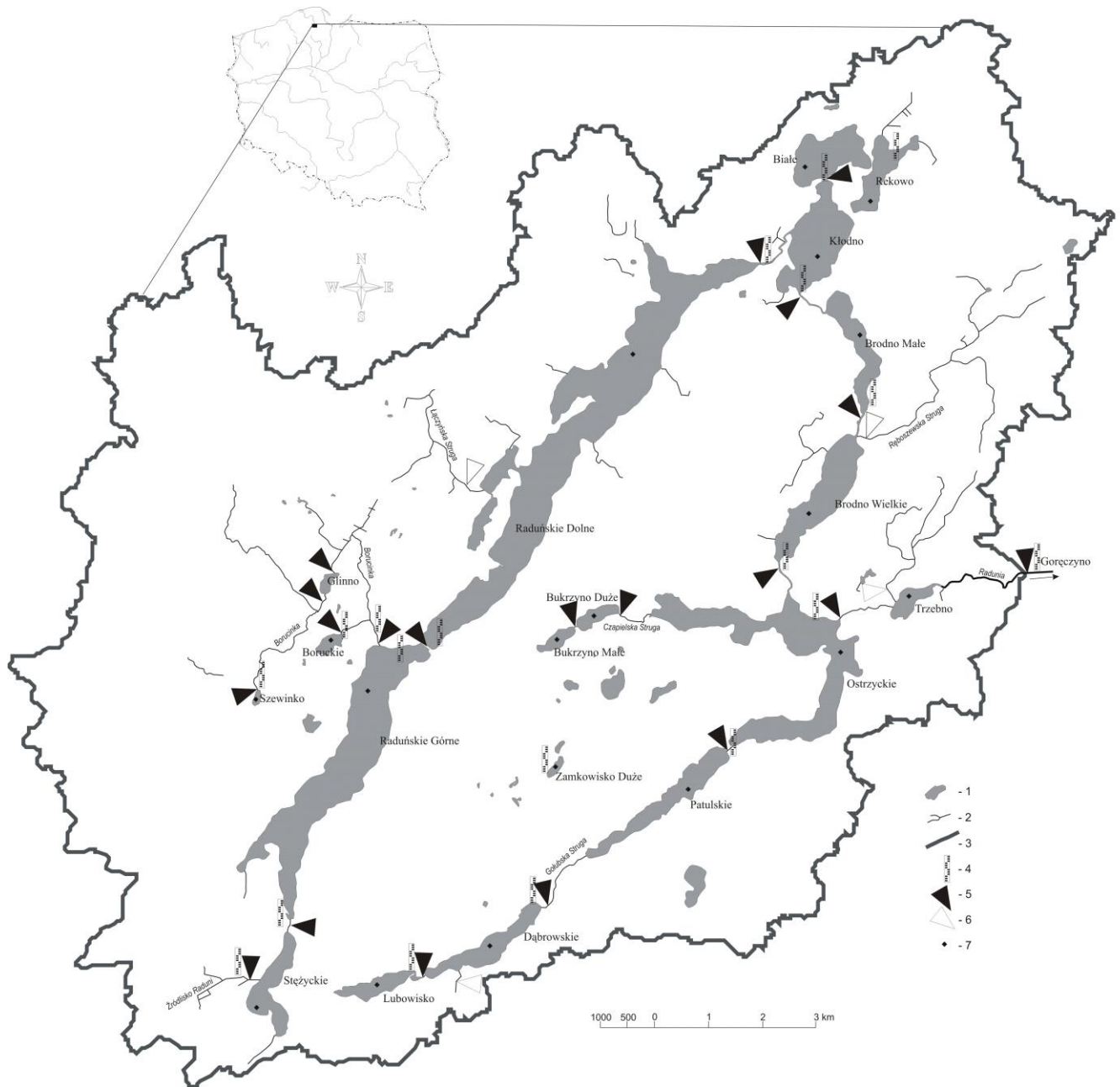
Conditions of the water cycle and the structure of the water supply to lakes are dependent on the location within the territorial hydrographic systems [Drwal 1982] as well as linear fluvial-lacustrine systems [Bajkiewicz-Grabowska 2002]. The location of a lake in the system determines the proportions between the surface and underground water supply and the ability of the water bodies to increase drainage. The water supply structure is responsible for changes in the properties of water in the lakes. The water in the surface phase of the cycle comes from various stages of the water circulation - from the precipitation to underground supply. The concentration of mineral substances contained in the water depends on the circulation time and the type of medium in which this circulation occurs. For this reason, the volume of water supply from various sources determines its mineralisation level.

The aim of the study is to show the relationship between the positions of lakes within the catchment with their supply structure, which in turn influences water conductivity.

## 2. METHODS

The object of the study was the fluvial-lacustrine system of the upper Radunia (Kashubian Lake District, Poland), which consists of 19 lakes (Fig. 1) differing in morphometric parameters, hydrological activity, resistance to outside influences, physico-chemical properties of water and trophic state. The time

range of the study covered the hydrological years 2000-2010, characterised by a significant diversity of annual course of the major hydrological and meteorological characteristics.



**Figure 1.** Upper Radunia catchment and the location of the gauging stations

Key: 1 - lakes, 2 - watercourses 3 - watershed of the upper Radunia catchment, 4 - gauging stations, 5 - basic hydrometric profiles, 6 - periodic hydrometric profiles, 7 - sites of limnological measurements

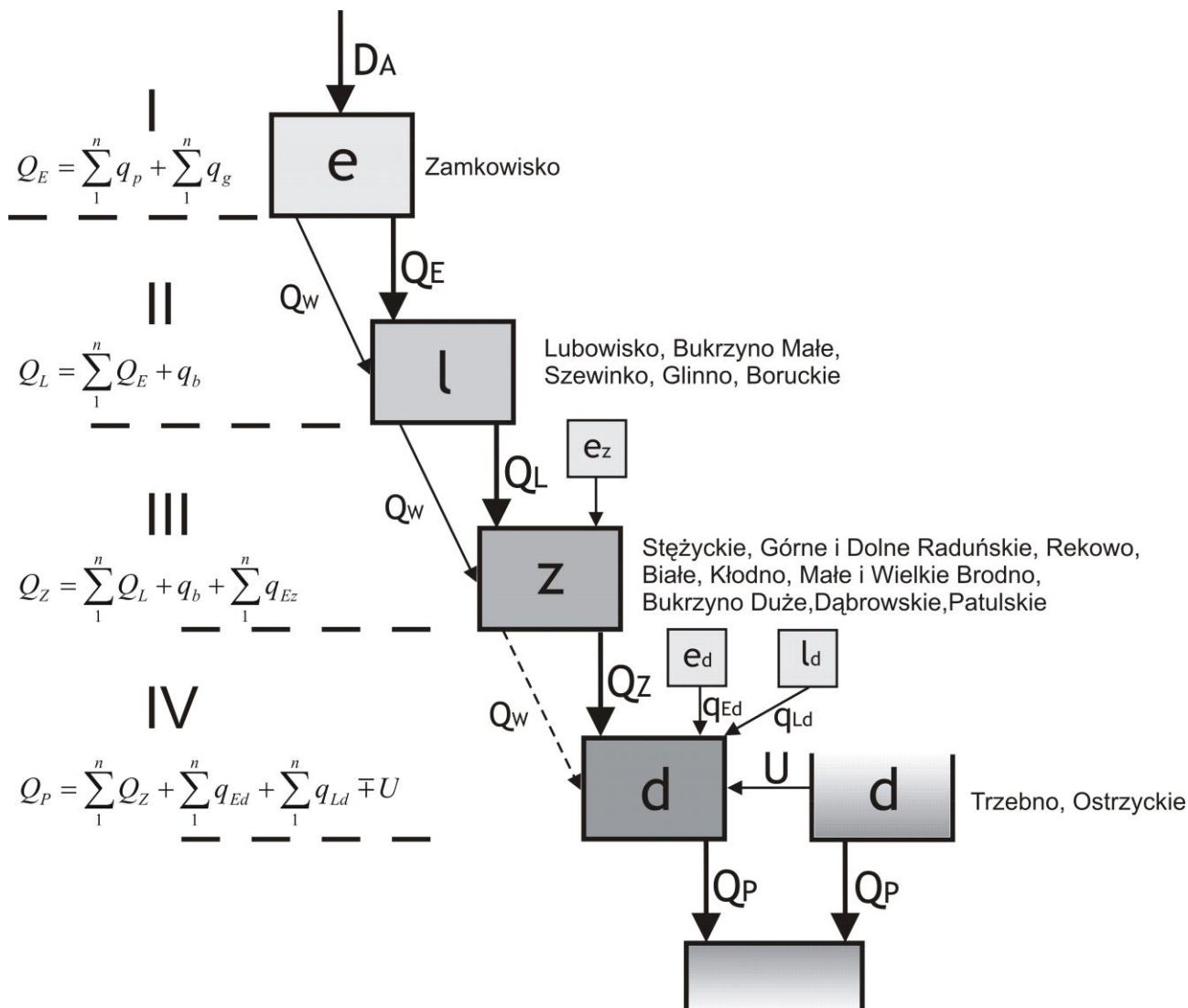
The series of monthly measurements included physical and chemical properties of the water in 19 lakes and 20 control sites located on the watercourses flowing into and out of lakes, where also flow measurements were performed. Recognition of the hydrological conditions of each lake was based on the hydrographic mapping of the catchment during the four main seasons of the year.

### 3. RESULTS

#### 3.1. Cascade system of the upper Radunia

Young-glacial areas form cascading catchments, where the water circulation and drainage is explained through the analysis of the development and organisation of the hydrographic network. In this approach a young-glacial catchment is considered to be a system of cascading and interconnected levels of the basin.

In the young-glacial hydrographic systems five interrelated levels of increasing degree of organisation can be distinguished (Fig. 2) [Drwal 1982]. The lakes within these levels differ in terms of their origin, morphometry, hydrological characteristics as well as their role in the system. Depending on the location at the level of the system, the lakes affect the conditions of water circulation across the system, from increasing evaporation, to the inclusion of groundwater into the circulation, to the initiation and regulation of potamic runoff [Drwal 1985].



**Figure 2.** Location of the lakes in the catchment of the upper Radunia at the levels of the hydrographic system

Key:

Levels of the system organisation: e - elementary catchments, l - local catchments, z - headwater catchments, d - river basins, n - number of units,  $e_z$  - elementary basins forming the catchment of the headwater watercourse,  $e_d$ ,  $l_d$  - elementary and local catchments forming the direct catchment of the main river.

Organisation levels of the river runoff:  $q_q$  - surface runoff from a unit of the elementary catchment,  $q_g$  - underground drainage from a unit of the elementary catchment,  $q_b$  - primary drainage,  $Q_W$  - underground drainage,  $D_A$  - atmospheric supply,  $Q_E$  - concentrated runoff from the elementary catchments,  $Q_L$  - runoff from the local catchment via watercourses,  $Q_Z$  - river runoff from the headwater catchments,  $Q_P$  - river runoff from the river basins, U - underground supply or runoff evening the water shortage or surplus between the river basins,  $q_{Ez}$  - concentrated drainage from the riverside headwater stream,  $q_{Ed}$ ,  $q_{Ld}$  - respectively, concentrated drainage from the elementary catchment and drainage of the local watercourse in the direct catchment of the main river

In the elementary units, where the first forms of concentrated runoff develop, there are small reservoirs (mainly kettle holes) mostly devoid of permanent drain. They occupy depressions which periodically accumulate excess water. In this area some of the water retained on the surface and under the ground returns to the atmospheric circulation, while some of the water infiltrates supplying the groundwater.

Within the borders of the elementary catchment there is an endorheic reservoir of Lake Zamkowisko, a large depth of which (17.8 m) suggests that it is connected with groundwater.

The criterion that allows classifying a unit into a higher level of the system organisation is the presence of permanent or periodic runoff. In the local catchments there appears the basic runoff thanks to the drainage of aquifers. At this organisation level the lakes provide river drainage. Lakes in the local catchments are larger than in the elementary catchments. They are supplied primarily by surface drainage of the catchment and groundwater drainage, which guarantees the stability of these objects and small potamic outflow. The lakes in the local catchments of the upper Radunia are Lakes Szewinko, Glinno, Boruckie, Bukrzyno Małe and Lubowisko (Fig. 2).

At a higher level of the system organisation, i.e. in the headwater catchments, there are the largest, flow lakes of large capacity. In the system of the upper Radunia these are Lakes Stężyckie, Raduńskie Górne, Raduńskie Dolne, Kłodno, Brodno Małe, Brodno Wielkie, Patulskie, Dąbrowskie, Rekowo, Białe and Bukrzyno Duże. These lakes take full part in shaping the river runoff, whose advantage over other forms of discharge of surplus water is a characteristic feature of headwater catchments. Due to their considerable depth, these lakes drain deep aquifers, including their water into the potamic circulation. In the headwater catchments there is also a noticeable delay in responding of the watercourses to the increased precipitation supply.

The next levels of the hydrographic system organisation in the young-glacial landscape are river basins, which mainly contain rheolimnic reservoirs, i.e. strongly flow-through lakes. The lakes of this type mainly store river water and function as regulators of runoff of the water supplied via the main river or directly from the headwater catchments. In this type of lakes the local factors play an insignificant role in the water cycle as the supply from the direct catchment of the lake is of little importance in the overall structure of the outflow. At this organisation level in the catchment of the upper Radunia there is Lake Trzebnio. Due to the storage of the water from different headwater, local and elementary catchments Lake Ostrzyckie can also be included in this level.

The highest level in the hierarchy which includes individual river basins is the Kashubian hydrographic system [Drwal 1985]. This fully developed system drains excess water from the Kashubian Lake District.

The cascading pattern of the hydrographic units is correlated with the morphological levels of the area. The plateau level is characterised by the periodic hydrographic network and the occurrence of endorheic areas. The bottoms of the channels show stability of the hydrographic network.

In the young-glacial areas the underground water circulation phase is of great importance. Based on the differences between the supply and runoff at the different organisation levels of the hydrographic network, it can be assumed that the underground water circulation can take place bypassing some aquifers. In this process the drainage role of lake basins is important. The lakes occurring at the different levels of the cascade, often of considerable depth, include the water from different aquifers in the surface circulation [Jankowska 1985]. In the elementary evapotranspiration catchments of the upper Radunia, after taking into account retention and the difference between precipitation and evaporation, the resultant underground discharge can reach up to 188 mm. In the elementary absorbent catchments the infiltration reaches 257 mm and is the main form of runoff from such units of the hydrographic system.

The surface runoff efficiency of the elementary drainage basins is mostly of 53-77 mm, which - after taking into account evaporation - gives the underground drainage at the level of 180-204 mm. Still larger groundwater supply occurs via the periodically drained catchments. In these units the surface runoff occurs only during wet seasons and therefore the annual total discharge via watercourses is 25 mm. The estimated underground discharge from the periodically drained basins is 232 mm, which is a huge source of supply for the hydrographic objects at the higher organisation levels.

### **3.2. Water conductivity**

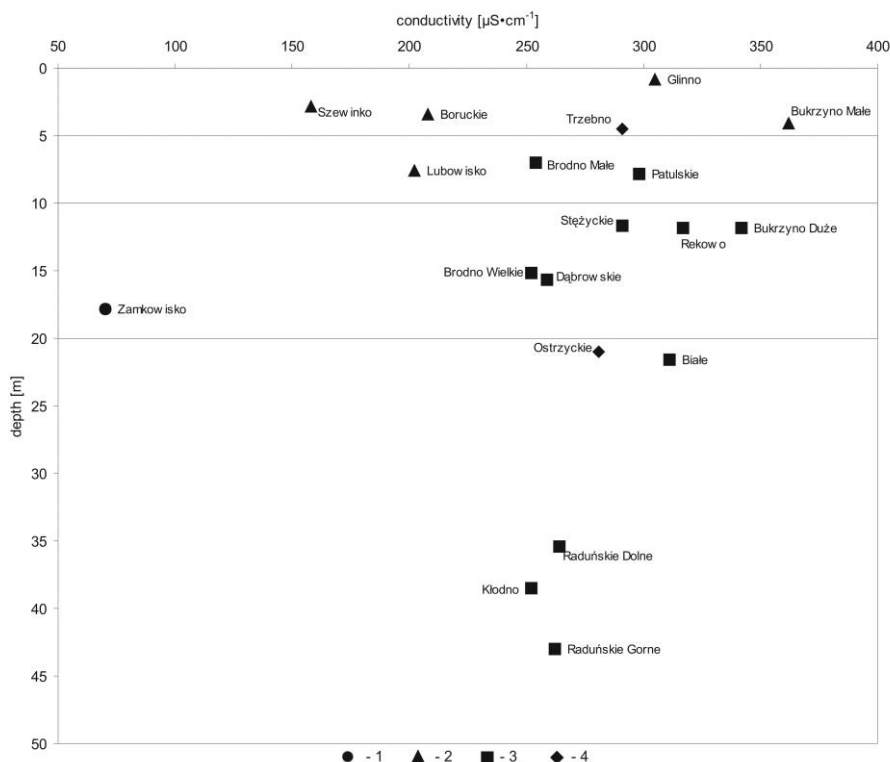
The supply structure of lakes is responsible for the properties of their water. The water in the surface phase of the water cycle is from various stages of the circulation, from precipitation to the underground supply. The amount of the contained mineral substances depends on the circulation time and the type of the medium in which it occurs. For this reason, the volume of water supplied from various sources determines the level of its mineralisation. The supply of the low-mineralised rainwater causes dilution and decreases concentrations of substances in surface waters. The infiltrating water transports substances from the surface to the groundwater, at the same time enriching its composition as a result of the dissolution of the mineral matter. Due to that the groundwater flowing out from the local and headwater catchments is significantly

contaminated, even despite partial filtration through the layers of sediments; the conductivity of this water is from 320 to 470  $\mu\text{S}\cdot\text{cm}^{-1}$ .

Short, often ephemeral watercourses in the catchment of the upper Radunia mostly display low conductivity of up to  $\approx 100 \mu\text{S}\cdot\text{cm}^{-1}$  (min  $85 \mu\text{S}\cdot\text{cm}^{-1}$  – the ephemeral watercourse opening to Lake Szewinko). With the development of the hydrographic network and a larger share of water supplied from deeper aquifers the water mineralisation increases in the watercourses of the upper Radunia; in their mouth sections the water conductivity reaches  $\approx 400 \mu\text{S}\cdot\text{cm}^{-1}$  (max  $430 \mu\text{S}\cdot\text{cm}^{-1}$  in the Struga Łączyńska). The conductivity of the lakes of the upper Radunia system is generally lower than that of the watercourses, which is due to the ability of lakes to transform matter. The conductivity values of the lake surface water range from  $\approx 70 \mu\text{S}\cdot\text{cm}^{-1}$  (Zamkowisko) to  $362 \mu\text{S}\cdot\text{cm}^{-1}$  (Bukrzyno Małe); the average for all the described lakes is  $259 \mu\text{S}\cdot\text{cm}^{-1}$ . The water of Lake Bukrzyno Małe reaches such high conductivity values due to the large share of the underground supply compared with other forms of supply.

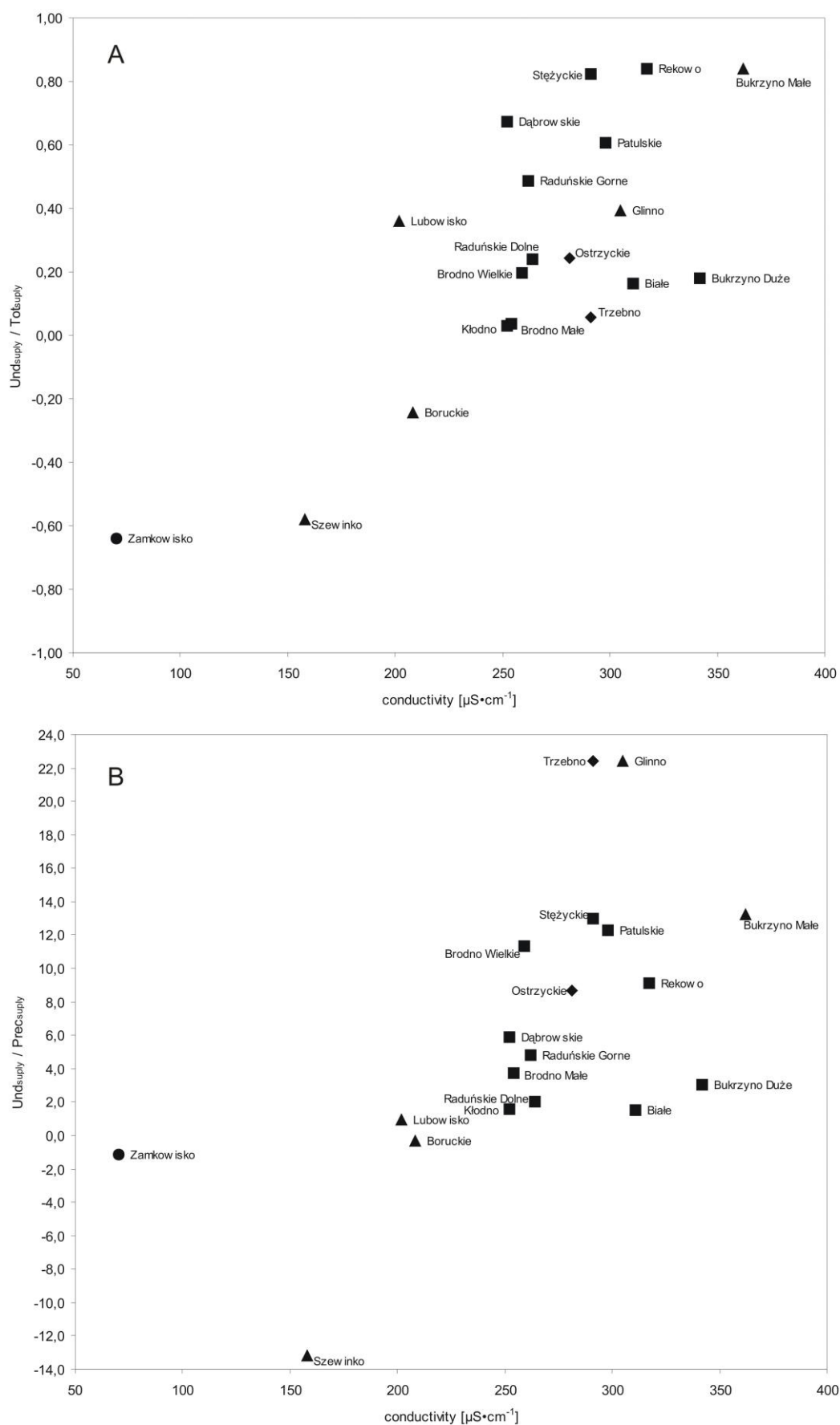
The groundwater supply into the lakes depends on many factors, including the predisposition of the lake basin to drain aquifers, which is determined by e.g. the maximum depth. Figure 3 shows the correlation between the maximum depth of the lakes at the different levels of the system organisation and the water conductivity. The figure indicates that the correlation between these elements is insignificant, while the location in a hierarchically organised hydrographic system is important. It is also noticeable that shallow lakes (mostly from local catchments) have the greatest diversity of conductivity: from  $158 \mu\text{S}\cdot\text{cm}^{-1}$  (Szewinko) to  $362 \mu\text{S}\cdot\text{cm}^{-1}$  (Bukrzyno Małe). The lakes of this type show a distinct predominance of one type of supply (e.g. surface supply in Lake Szewinko, fluvial supply in Lake Glinno and underground supply in Lake Bukrzyno Małe), which determines the water mineralisation.

The water conductivity of the medium-depth lakes ( $H_{\text{max}}$  5-10 m) in the headwater catchment does not show a large variation, ranging from 250 to  $300 \mu\text{S}\cdot\text{cm}^{-1}$ . Lake Lubowisko, located in the local catchment, has a lower conductivity ( $202 \mu\text{S}\cdot\text{cm}^{-1}$ ), which is caused by a larger role of precipitation in its supply structure. A similar situation is observed in the case of deep lakes in the elementary catchment. Lake Zamkowisko is mainly supplied via precipitation and the conductivity of its water is only  $70 \mu\text{S}\cdot\text{cm}^{-1}$ . The water of deep and very deep lakes in the headwater catchments and river basins do not show a large variation of conductivity, but its value is also dependent on the contribution of different sources of supply.



**Figure 3.** Correlation of water conductivity and the maximum depth of lakes

Key: 1 - lakes in the elementary catchment, 2 - lakes in the local catchment, 3 - lakes in the headwater catchment, 4 - lakes in the river basin



**Figure 4.** Correlation of water conductivity and the underground supply relative to the total water supply to the lakes (A) and the ratio of the underground supply to the precipitation supply (B)



The proportions between the various components of supply, namely the volume of the underground, surface and precipitation supply, affect the chemical composition of the water, which is reflected via its conductivity. The correlations of conductivity and the underground and total supply quotient ( $Und_{supply} / Tot_{supply}$ ) as well as the ratio of the underground and precipitation supply ( $Und_{supply} / Prec_{supply}$ ), represented in Figures 4 A and 4 B, show the dependency of mineralisation on the source of the water supply in lakes.

The biggest participation of the resultant underground supply in the total supply to the lakes ( $Und_{supply} / Tot_{supply} \approx 0.8$ ) is recorded in Lakes Stężycie, Rekowo and Bukrzyno Małe. Such a large supply with the underground water of higher mineralisation increases water conductivity in these lakes. The reservoirs in which the underground drainage is found ( $Und_{supply} / Tot_{supply} < 0$ ) show the lowest water mineralisation. These are mostly lakes in the elementary catchments (Zamkowisko) or some shallow lakes in the local catchments (Szewinko). The exception is Lake Boruckie, which, despite the advantage of the precipitation supply and underground runoff, shows an average conductivity of  $208 \mu S \cdot cm^{-1}$ . This condition is caused by severe anthropopressure exerted on this water body.

In the other lakes of the upper Radunia the participation of the underground supply ranges from 3-4% (Kłodno, Brodno Małe) to over 60% (Patulskie, Dąbrowskie). With the varying influence of surface and precipitation supply this causes the differentiation of the water mineralisation. Moreover, the ratio of the water from the underground resources to the precipitation supply variability explains the conductivity of the water in this group of lakes (Fig. 4 B). In most of the lakes of the upper Radunia the impact of these supply sources on the mineralisation of water is visible. The lakes whose water conductivity depends mainly on the surface supply (Bukrzyno Duże, Białe, Brodno Wielkie, Trzebnio, Glinno) are the most deviating from the scheme. Lakes Szewinko, Zamkowisko and Boruckie have a negative indicator and the more the underground runoff exceeds the precipitation volume, the smaller the value.

### 3. CONCLUSIONS

An important role in shaping the properties of water, including conductivity, is the location of the lakes in the hierarchically organised hydrographic system as well as the supply structure of the lakes in conjunction with the morphometric characteristics of the lake basins. These correlations allow us to conclude the following:

- In terms of the supply conditions and water mineralisation, a greater role is played by the location in a hierarchically organised hydrographic system than the maximum depth of the lakes.
- The total mineralisation of the lake water is correlated with the ratio of the underground supply and the overall supply ( $Und_{supply} / Tot_{supply}$ ) and the ratio of the underground supply and precipitation supply ( $Und_{supply} / Prec_{supply}$ ). The variability of the characteristics of the  $Und_{supply} / Tot_{supply}$  in the lakes of the upper Radunia ranges from the negative values (underground discharge) in Lakes Zamkowisko, Szewinko and Boruckie, and below 0.1 (Kłodno, Brodno Małe, Trzebnio) to over 0.8 (Bukrzyno Małe, Rekowo, Stężycie). The values of the other correlation ( $Und_{supply} / Prec_{supply}$ ) also take negative values in the lakes with the underground drainage. In the remaining lakes range from 1 (Lubowisko) to more than 10 in Lakes Brodno Wielkie, Patulskie, Stężycie, Bukrzyno Małe, Glinno and Trzebnio.
- Shallow lakes ( $H_{max} < 5$  m), located mostly in local catchments, show the greatest diversity of water conductivity: from  $158 \mu S \cdot cm^{-1}$  (Szewinko) to  $362 \mu S \cdot cm^{-1}$  (Bukrzyno Małe). The lakes of this type show a distinct predominance of one type of supply (e.g. surface supply in the case of Lake Szewinko, fluvial supply in Lake Glinno and underground supply in Lake Bukrzyno Małe), which determines water mineralisation. Lake Bukrzyno Duże has a very large participation of the underground supply in the total supply of water to the lake ( $Und_{supply} / Tot_{supply} \approx 0.8$ ), while in Lake Szewinko there was no groundwater supply ( $Und_{supply} / Tot_{supply} < 0$ ).
- The water conductivity of the medium-depth lakes ( $H_{max}$  5-10 m) at the level of the local catchment is  $\approx 200 \mu S \cdot cm^{-1}$  (Lubowisko), which reflects the greater importance of precipitation in the supply structure (underground supply to precipitation supply  $Und_{supply} / Prec_{supply} = 1$ ). The water conductivity of the medium-depth lakes at the level of the headwater catchment range from  $250 \mu S \cdot cm^{-1}$  (Brodno Małe) to  $300 \mu S \cdot cm^{-1}$  (Patulskie), which reflects an increase in the importance of surface supply in the case of Lake Brodno Małe and the underground supply in Lake Patulskie ( $Und_{supply} / Tot_{supply} = 0.61$ ).
- The water conductivity of the deep lakes ( $H_{max}$  10-20 m) located at the level of the headwater catchments ranges from  $260 \mu S \cdot cm^{-1}$  (Brodno Wielkie) to  $340 \mu S \cdot cm^{-1}$  (Bukrzyno Duże). The mineralisation of these lakes is mainly due to water supplied from the lake above, while the importance of the underground supply is evident in the case of Lakes Rekowo and Stężycie where  $Und_{supply} / Tot_{supply} \approx 0.8$ . Lake Zamkowisko, at

the level of the elementary catchment and supplied predominantly via precipitation, despite its considerable depth, shows no underground supply ( $Und_{supply} / Tot_{supply} < 0$ ), resulting its water conductivity of  $\approx 70 \mu S \cdot cm^{-1}$ .

- The very deep lakes ( $H_{max} > 20$  m) at the level of the headwater catchments and river basins do not show a large variation of conductivity, which ranges from  $250 \mu S \cdot cm^{-1}$  (Kłodno) to  $310 \mu S \cdot cm^{-1}$  (Białe). In the lakes at this level of the territorial hydrographic system the importance of surface supply increases at the expense of the underground supply ( $Und_{supply} / Tot_{supply}$  ranges from 0.03 to 0.16).
- Lake Boruckie, despite the advantage of the precipitation supply and underground runoff, shows an average conductivity of  $208 \mu S \cdot cm^{-1}$ . This condition is caused by a severe anthropopressure exerted on this water body.

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