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SENSITIVITY OF A LARGE FLOW-THROUGH LAKE TO METEOROLOGICAL CONDITION AND ANTHROPOGENIC STRESS (HYDROMORPHOLOGICAL ASSESSMENT)

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Abstract

The paper refers to the contemporary sensitivity of a ribbon flow-through lake to changeable meteorological conditions (precipitation, evaporation). We checked whether the lake morphology can affect the abrupt changes in hydrological conditions under which environmental changes occur. We analyzed changes in the level and extent of the water table in relation to morphological thresholds of a Charzykowskie Lake. Changes in the lake water level were disproportionate in relation to small changes in the volume of water involved in the exchange. During 55 years of observations, the lake water level did not exceed the threshold values of sensitivity to shortage or surplus stress.

Key words

climate change • flow-through lake • Charzykowskie Lake • lake morphometry • lake sensitivity • natural resources management • physical limnology

Introduction

In the era of debate on the protection of natural resources and the prevention of adverse climate change (global warming – Parry et al. 2007), an increasing emphasis is being placed on the management of lake resources (George 2010; Servos et al. 2013). Limnologists often underline the fact that lakes are not stable elements and tend to disappear through the effect of many different processes. The rate of lake disappearance has increased (Gąsiorowski 2008; Marszelewski et al. 2011), and the area of Polish lakes has decreased by proportions varying from 9.60% on Pojezierze Pomorskie to 15.21% on Pojezierze Wielkopolsko-Kujawskie (Choiński 2006). The tempo and direction of these processes depend, in natural conditions, on climate fluctuations, sedimentation and vegetation encroachment ratios, and changes in the drainage basin of the flow-through lakes (Choiński & Ptak 2008; Ławniczak 2010; Marszelewski et al. 2011). Many scientists (Bajkiewicz-Grabowska 2001; Michalczyk & Turczyński 2001; Górniak & Piekarski 2002; Dąbrowski 2004; Choiński 2007; Choiński & Ptak 2008; Ptak et al. 2013) underline the importance of local conditions in lake transformations. This is, in many cases, caused by the unwitting effects of human management – e.g. deforestation, the development of agriculture, groundwater abstraction (Churski 1983; Kaniecki 1997; Choiński et al. 2012). On the other hand, there is the possibility of undertaking activities to protect the water resources, e.g. damming lakes, water transfers, etc.

An important step in planning protective measures and adaptations to changing conditions is to understand the contemporary hydrological sensitivity of the lake to adverse meteorological conditions that cause shortages or surpluses of water (droughts/floods) (Australian Greenhouse Office 2005; Soja et al. 2012). For this purpose, we have studied two elements determining the hydrological status of the lake: the level and the range of the water surface (McParland & Barrett 2009; Laprida et al. 2014). The selected hydrological characteristics affect the growth of macrophytes (Keddy 1990; Ostendorp 1991), invertebrates (Smith et al. 1987; Baumgärtner et al. 2008; Brauns et al. 2008), ichthyofauna (Fischer et al. 2004; Yamamoto et al. 2006; Sutela & Vehanen 2008), birds (Hake et al. 2005; Desgranges et al. 2006) and, indirectly, the trophic status of the lake (Hellsten & Dudley 2006; Paillisson & Marion 2011). They are therefore a very important indicator of the impact exerted by climate change and anthropopressure on ecological condition (Water Framework Directive)[1]. At the same time, using conclusions expressed by Wantzen et al. (2008), we have assumed that the response of the lake system to water fluctuations depends on the morphology of the lake basin. This means that the shape of the lake basin is an important factor controlling the reaction of the lake to changeable meteorological conditions (precipitation, evaporation) and human impact. Many authors (e.g. Pasławski 1975; Jańczak 1991; Lange 1993; Choiński 2007; Grandke 2009; Choiński et al. 2011; Ptak et al. 2013; Kramkowski et al. 2014; Kutyła 2014) indicate relationships between lake water level changes and lake bowl parameters such as its area, depth and volume. This paper considers other aspects of this phenomenon.

Considering the diverse shapes of lake basins (thresholds dividing the lake into parts, variable shape of the shore zones and slope) we assumed that with different filling of the lake bowl with water the morphology can affect the abrupt changes in environmental conditions. Therefore, we decided that the combination of morphological and hydrological information is a very important medium of the impact of extreme meteorological conditions on the ecological condition of the lake.

During our research, we checked if the observed temporary droughts and wet periods may affect the abrupt environmental changes in the flow-through ribbon lake with a large catchment. The authors also considered the possibility of the lake water damming up to the maximum water level determined by the conditions of periglacial lake trough formation. The pilot studies were conducted on the example of Charzykowskie Lake located in the Tuchola Forest Biosphere Reserve in Poland, where flow-through ribbon lakes play an important natural function. To assess the hydrological sensitivity of the lakes we established the altitudes of the morphological thresholds of the lake basin (m a.s.l.), the surpassing of which by the water's surface induces environmental changes such as: intensified abrasion and sediment resuspension, drying or expansion of the littoral and connection with other lakes (Australian Greenhouse Office 2005). We compared them with the multiannual (1961-2015) observations of the

[1] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.

water level in the studied water body against the diversity of rainfall in this period.

To carry out a deeper investigation into this topic, the authors used the advantages of GIS software for lake bowl 3D modelling. This was useful in identifying the morphological steps dividing the lake trough, establishing the changes of the lake bed slope and the bowl shape, and the drainage base in the flow-through lakes. In order to assess the representativeness of the results for a comparative study, we compiled the water balance of the lake in the years 1974-2015.

Methods

Study area

We selected for the study Charzykowskie Lake, which is one of the largest early post-glacial lakes in Poland (Choiński 2006). The lake is located in the South Baltic Lake District where the climate is influenced by the Atlantic Ocean and the Baltic Sea. It plays an important role in the protection of the landscape and natural values of the Pomeranian Lake District. In 2010, it was included in the core zone of the Tuchola Forest Biosphere Reserve. Furthermore, it is included in the Zaborski Landscape Park (ZPK), in the buffer zone of the Tuchola Forest National Park (PNBT), and the Special Protection Area for Birds „Wielki Sandr Brdy" (PLB220001; Natura 2000). Fragments of the direct catchment of the lake are defined as Special Areas of Conservation. The lake is of great importance for recreation, water sports and nature-based tourism. It serves as a weekend base for the town of Chojnice, with 40,000 inhabitants. The lake's resources are used in fishery and angling.

Charzykowskie Lake fills a large ribbon (Fig. 1). The ribbon was formed as a result of complex geomorphological processes occurring from Krajeńska subphase of the Vistula glaciation (16,800 BP) to nowadays (Galon 1953; Pasierbski 1975; Nowaczyk 1994; Kozarski 1995).

The water level in the lake ribbon changed many times during its formation. Initial changes could be connected to the process of ablation of dead ice blocks and the changes of the drainage level of the newly forming Brda river system (Błaszkiewicz 2007). The lake area was the largest in about 12,700 BP (Nowaczyk 1994). The later periods brought a decrease in the areal extent of the lake (Nowaczyk 2006) together with a lowering of the drainage base accompanied by delta accumulation in the Brda and climate change (Szeroczyńska & Zawisza 2011). The present lake water level is about 3.0-3.8 m lower. Nowadays the ribbon is filled with 4 lakes. Besides the Charzykowskie Lake these lakes are: Długie, Karsińskie, and Mielnica (Fig. 1).

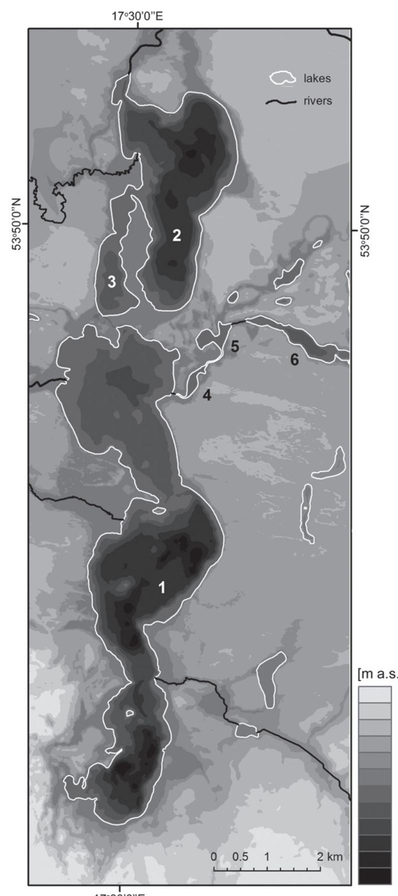

Figure 1. Topography of the Charzykowskie Ribbon. Lakes: 1 – Charzykowskie, 2 – Karsińskie, 3 – Długie, 4 – Mielnica, 5 – Skrzynka, 6 – Płęsno

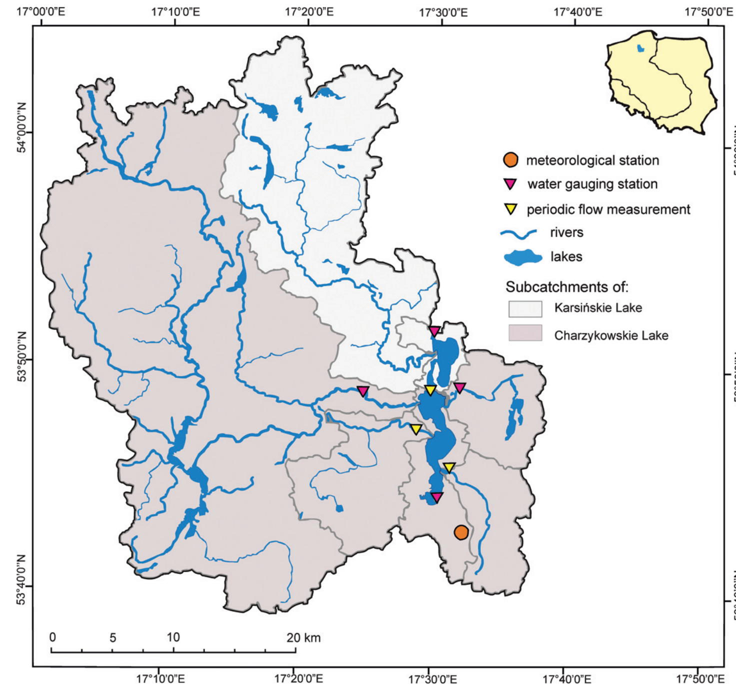

Figure 2. Hydrographic division of the basin of the Charzykowskie Ribbon

Charzykowskie Lake has a compact shore line (over 32.6 km in length). The maximum depth is 29 m (average depth of 10 m). The total area of the lake (1349 ha) represents only 1.5% of the catchment area (920 km^2). A large river – Brda – flows through the lake (on average 6 m$^3 \cdot$s^{-1}), together with a few smaller rivers and streams with a stable natural regime (Choiński 2002) (Fig. 2).

Identification of morphological thresholds

The Charzykowskie Ribbon is complex and consists of: a high shoreline cliff, a narrow shorezone, a large slope gradient (up to 23°) and high morphological step dividing the ribbon into pools. Following these premises, we considered three threshold values for the water level which, if exceeded, cause an abrupt change in the water turnover conditions, as well as in morphological and ecological processes (Fig. 3). These are 123.5 m a.s.l., 121.5 m a.s.l. and 118.7 m a.s.l. In the first case (threshold I), Charzykowskie Lake would fill the entire ribbon and would merge with the neighbouring lakes (Fig. 4).

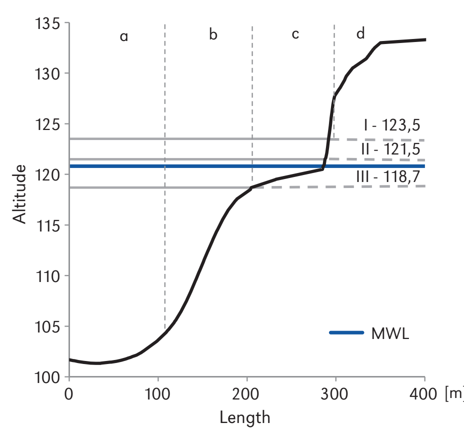

Figure 3. Threshold values (I-III) of the water level against the morphological structure of the lake basin: a – pool; b – slope; c – shorezone; d – slope of the basin; MWL – mean water level in 1961-2010 (120.10 m a.s.l.)

The adopted water level (123.5 m a.s.l.) reflects the maximum water level in the lake in the geological period following deglaciation, so the initial stage of the lake functioning (Tołpa 1950; Nowaczyk 2006) (Fig. 3, 4). Charzykowskie Lake was then connected with smaller reservoirs in the northern part of the ribbon (Karsińskie Lake and Długie Lake) and with the lake located to the north-east (Gałka 2006) (Fig. 2). Although present forecasts of climate change do not indicate a repeat of scenarios of these kinds, there is a possibility of reaching such conditions by artificially damming the lake to store water for dry periods. Ideas of this kind were reported even as recently as the 1990s (Fal & Bogdanowicz 2002). Such conditions would cause an increasing role of waves and therefore the abrasion of the north-eastern parts of the lake shore and the resuspension of lake bed deposits. The conditions of water mixing would also be changed leading to a shallowing of the hypolimnion in the northern part of the reservoir.

The rise of the water above 121.5 m a.s.l. is followed by the water table rising up to steep shoreline escarpments and enhanced abrasion processes of the shorezone as a result of wave motion. The topography of the lake basin was taken into account in the determination of these thresholds (slope gradient >6°,

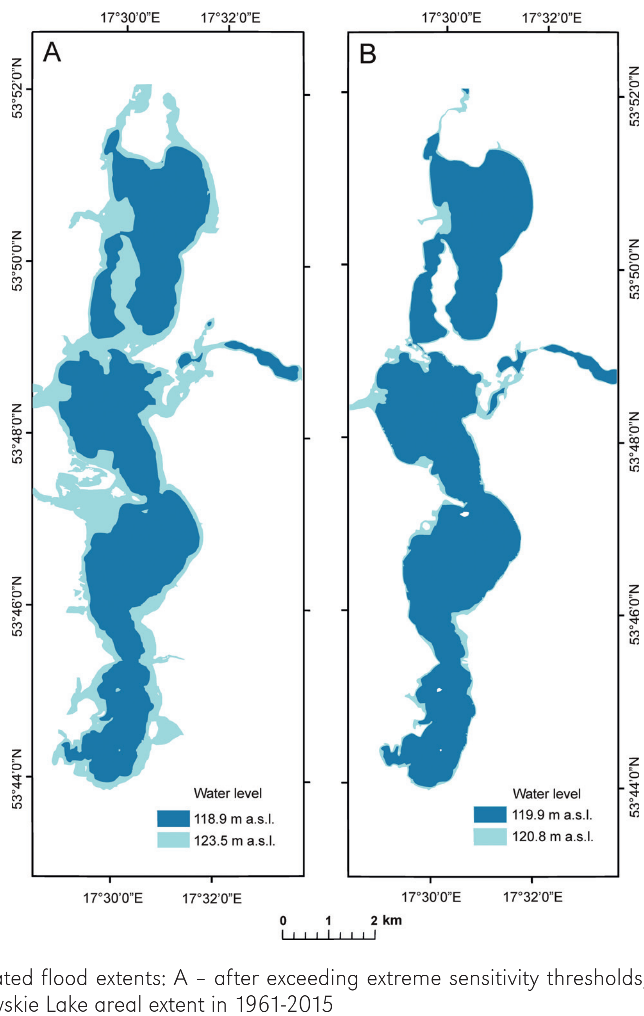

Figure 4. Simulated flood extents: A – after exceeding extreme sensitivity thresholds; B – the changes of the Charzykowskie Lake areal extent in 1961-2015

which defines zones prone to erosion and the boundary of the shorezone).

The third case considered assumed that the water level would be lowered to the present drainage base (118.7 m a.s.l.) which would cause the stopping of surface outflow from Charzykowskie Lake accompanied by the exposure of the littoral zone. This can involve serious ecological consequences, as identified by several studies (Schmieder 2004; Havens & Gawlik 2005; Yamamoto et al. 2006; Hofmann et al. 2008; Wantzen et al. 2008; Zohary & Ostrovsky 2011), and changes in the management of the shoreline zones, e.g. a change in the beach range, or the necessity to change the length of piers (Padisák et al. 2006).

Threshold values were determined based on geodetic profiles and a digital elevation model (DEM) of the lake basin relief (Fig. 1). The DEM model of the lake ribbon was created by combining the bathymetric plan and the topographic map (scale of 1:10,000), and geodetic data collected in the shorezones (developed by IMGW-PIB 2012). The resolution of the DEM is 1 m. Simulations of the range and calculations of the morphometric characteristics of the lake at different water levels (Fig. 3) were performed with the software ArcGIS ver. 10.2.

A priori determined sensitivity thresholds of the lake system to changes in the lake basin filling were related to contemporary water-level fluctuations in Charzykowskie Lake, observed over the period 1961-2015.

Assessment of meteorological conditions

In order to assess the representativeness of the results, we analysed the variability of the water level in Charzykowskie Lake in relation to mean monthly temperature and monthly precipitation values expressed by the Standardized Precipitation Index (SPI) (McKee et al. 1993). Monthly total precipitation values P_t [mm] were normalized with the transformation function F(P) (Bąk & Łabędzki 2002):

$$F(P) = P_t^{-\frac{1}{3}} \tag{1}$$

SPI values for a given P were calculated from the equation:

$$SPI = [F(P) - \mu]\sigma^{-1} \tag{2}$$

where: F(P) – the transformed sum of precipitation; μ – the mean value of the normalized precipitation sequence; σ – the standard deviation of the normalized precipitation sequence.

Water exchange balance

The assessment of the effect of atmospheric factors on the conditions of water exchange in Lake Charzykowskie was based on the modified water balance formula (Mikulski 1970). The formula considers three exchange components: atmospheric ($P_{\Delta t}$ - $E_{\Delta t}$), fluvial ($Hri_{\Delta t}$ - $Hro_{\Delta t}$) and groundwater ($\Delta Hg_{\Delta t}$):

$$R_{t+1} - R_t = (P_{\Delta t} - E_{\Delta t}) + (Hri_{\Delta t} - Hro_{\Delta t}) + \Delta Hg_{\Delta t} \tag{3}$$

where: R_t and R_{t+1} – state of retention at the beginning and end of the balance period, $P_{\Delta t}$ – precipitation on the lake's surface area, $E_{\Delta t}$ – evaporation from water surface, $Hri_{\Delta t}$ – fluvial inflow to the lake, $Hro_{\Delta t}$ – fluvial outflow from the lake, $\Delta Hg_{\Delta t}$ – resultant of underground exchange.

The assessment of atmospheric exchange in the studied lake was based on hydrometeorological data from the synoptic station in Chojnice and observations of ice cover on the Charzykowskie Lake. Precipitation totals on the lake surface area were calculated based on measurements of daily totals. Monthly evaporation totals were calculated from empirical formulas applying easy to measure meteorological parameters. In the case of the occurrence of ice cover on the lake, the Iwanow's formula was applied (following Kędziora 1995):

$$E = 0.0018(25 + T)^2\,(100 - f) \tag{4}$$

where: T – air temperature, f – relative humidity.

Evaporation from open water surface was calculated in the function of deficit of humidity (d), the number of days per month (i) and wind velocity at the altitude of 2 m (v_2), based on the Penman's empirical formula (1948):

$$E = 0.36\,d\,i\,(1 + 0.5v_2) \tag{5}$$

Both of the formulas were verified in northern Poland. It is presumed that at the monthly scale, they provide results in accordance with the intended results (Kędziora 1995; Dąbrowski 2007; Walkusz & Jańczak 2007). For the purpose of facilitating comparative analyses, changes in retention were calculated in relation to the state of the lakes as at 1 December 1998. Inflow and outflow from the lake was calculated based on the Brda daily discharges (Profile Ciecholewy and Swornegacie) and the regression dependencies between the discharge of the Brda River (at the inflow and outflow from the lake), and the remaining tributaries (Czerwona Woda, Struga Siedmiu Jezior, Jarcewska Struga) (Fig. 2).

The last component (the resultant of groundwater exchange) is calculated from the balance difference. The resultant of underground exchange is positive when the lake fulfils the draining function in the balance period, and negative when it constitutes a source of alimentation of underground waters (Bajkiewicz-Grabowska 2002).

The balance calculations were conducted with a monthly time step Δt. The resulting data were aggregated to periods of hydrological year (from November to October). The calculation unit was water layer in million m^3 and mm in relation to the lake's surface area. The balance calculations were conducted for a period of 35 years (1974-2015).

Measurement data

The analysis involved the application of materials from verified digital databases of the Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB). They were daily water levels in Lake Charzykowskie from the water gauge of IMGW-PIB in Charzykowy for the years 1961-2015 (Fig. 2). Observations and measurements conducted at hydrometric gauges of IMGW-PIB located on the Brda River above Lake Charzykowskie in cross-section Ciecholewy, and below another lake filling the Charzykowy ribbon in cross-section Swornegacie for the period 1974-2015 were also used. The assessment of atmospheric exchange in the lake studied was performed based on hydro-meteorological data from the synoptic station of IMGW-PIB in Chojnice. The station is located approximately 2.7 km south-east of Lake Charzykowskie, approximately 20 m above the water surface. Also, we had discharge measurements that were conducted irregularly on the other tributaries of Lake Charzykowskie. These include measurements carried out by the Department of Hydrology Faculty of Geography Warsaw University, and carried out by Voivodship Inspectorate for Environmental Protection in Bydgoszcz in 1997 and the others that are in the database of the Zaborski Landscape Park.

Results

The reference period chosen for the studies was characterized by: (1) a long-term, positive trend in the mean annual air temperature; (2) the absence of long-term trends in the total annual rainfall recharge; (3) large differences in precipitation; (4) extreme variation in the total monthly rainfall recharge over time (Fig. 5). The late 1980s and early 1990s stood out against this backdrop. A long term hydrological drought (reduction of water resources) took place throughout Poland, the effects of which were visible until 1996 (Fal & Bogdanowicz 2002). Since the beginning of the 21st century a very large diversity of monthly precipitation totals has been observed - extremely dry months interspersed with extremely wet. This lasted until 2012. From this year on significantly low precipitation and heat waves occurred in the summer period (Fig. 5). In 2015 a severe drought occurred.

Water exchange in Lake Charzykowskie is very high. In 1974-2015, during the hydrological year (XI-X), an average of 253 million m^3 of water was involved in the exchange. This is 1.8 times more than the water resources of the lake (139 million m^3). In subsequent years this figure varied widely, from 320 million m^3 to 190 million m^3 in the extremely dry year (2015). The atmospheric component of exchange was negligible and accounted for only about 2% of lake water resources

($(P_{\Delta t} - E_{\Delta t})$ = -0.3 million m^3). This component was characterized by a predominance of evaporation over precipitation (Tab. 1).

Because of this, in 1974-2015 the sum of atmospheric exchange deficits reached -12 million m^3. Annually, the balance of precipitation and evaporation exchange on the lake surface changed within the range of -6 (2015) to +6 million m^3 (1980). In the spring and summer months, despite a marked increase in precipitation, there was a negative difference in the atmospheric balance. This situation lasted from April to September. Shortages of the atmospheric supply in the summer half-year were partially supplemented in the autumn-winter period.

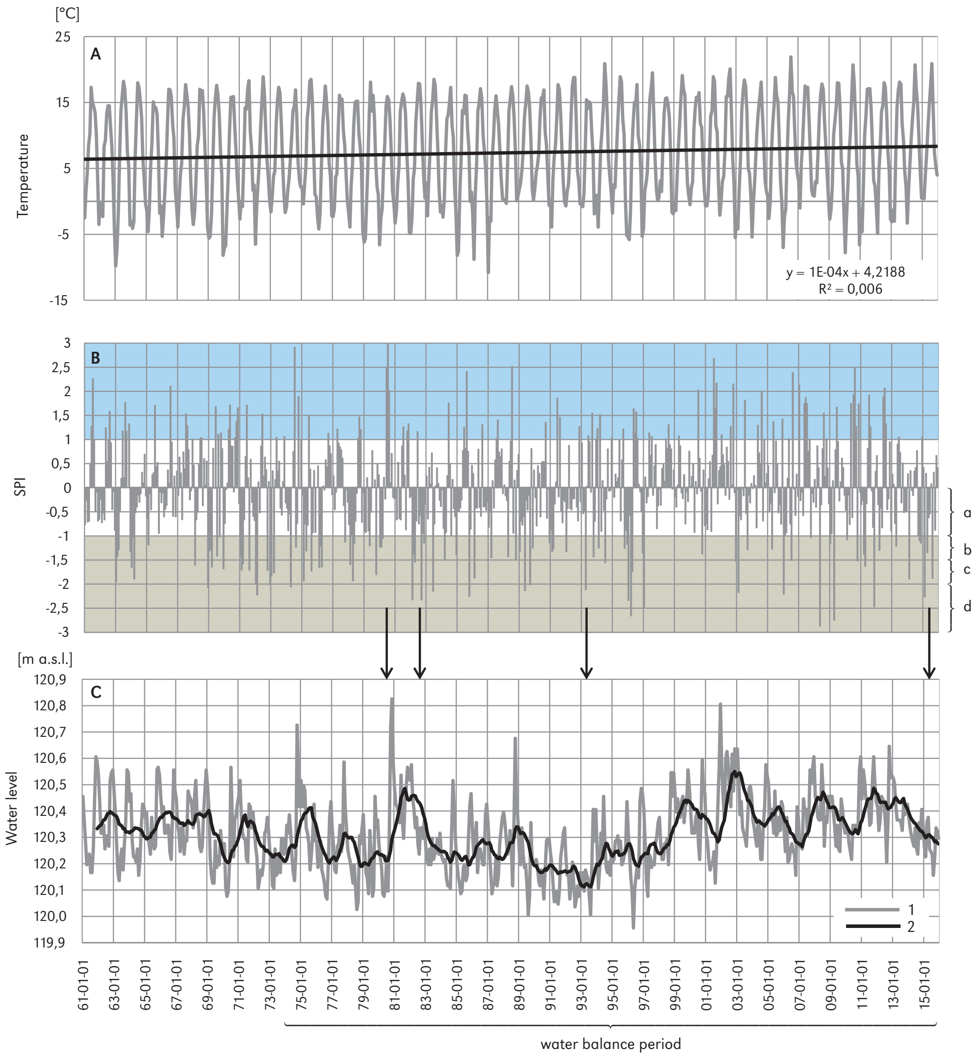

Figure 5. Effect of air temperature and precipitation conditions on changes in the water level in Charzykowskie Lake: A – mean monthly air temperature; B – monthly values of the Standardized Precipitation Index (SPI), a – mild drought, b – moderate drought, c – severe drought, d – extreme drought; C – water level fluctuations in Charzykowskie Lake in monthly intervals (curve-1) in relation to the 24-month moving average (curve-2). Arrows indicate the years analysed in detail

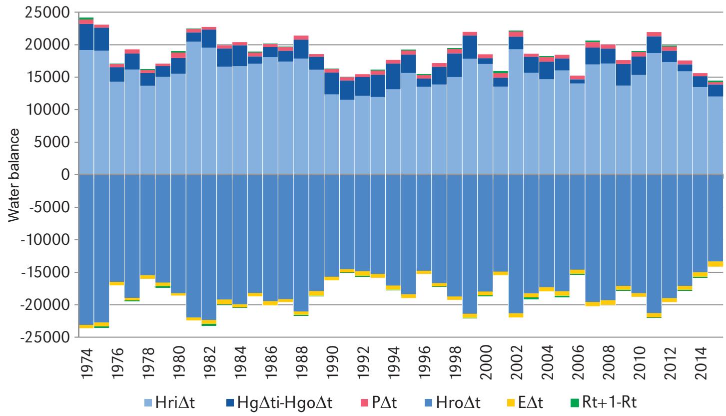

Figure 6. The water balance structure of Charzykowskie Lake in 1974-2015

Table 1. Balance of water exchange (million m^3) in Charzykowskie Lake in the extreme years on the backdrop of the average values of 1974-2015

Hydrological year (X-XI)	Atmospheric exchange	Fluvial exchange	Groundwater exchange	Difference of retention
	$P_{\Delta t}$ - $E_{\Delta t}$	$Hri_{\Delta t}$ - $Hro_{\Delta t}$	$Hg_{\Delta ti}$ - $Hgo_{\Delta t}$	R_t - R_{t+1}
Average of period	-0.3	-31.5	31.8	-0.1
1980 – extremely humid	6.1	-35.6	32.4	-2.8
1982 – with the highest increase of retention	-3.3	-37.3	37.3	3.4
1993 – hydrological drought	0.7	-44.1	45.5	-2.0
2015 – extremely dry	-5.5	-17.2	24.7	-2.0

A more important component of the Charzykowskie Lake water balance is fluvial exchange. In the analysed period it constituted over 40% of the water involved in the circulation. The average annual river inflow to Charzykowskie Lake amounted to 212 million m^3 (Fig. 6, Tab. 1). Inflow to Charzykowskie Lake is determined by Brda River (89% of river inflow to the lake), and to a lesser extent, by 3 tributaries: Jarcewska Struga (6%), Czerwona Struga (3%), Struga Siedmiu Jezior (2%).

Despite the lowland character of the tributaries, characterized by a relatively balanced regime (Choiński 2002), the reaction of rivers to atmospheric forcing was clear. The largest inflow of river occurred in 1981 and amounted 276 million m^3. In 1991, during the hydrological drought, it was 1.8 times lower. Throughout the study period the balance of the fluvial exchange was negative. River outflow was greater than inflow by an average of 32 million m^3.

Groundwater recharge plays an important role in refilling the lake's water resources. The underground water turnover is supported by a sandy littoral and facilitated by the location of the lake ribbon and its contact with the subterranean Quaternary waters (headwater zones). In a hydrological year groundwater inflow represents averagely 23% of the lake resources (32 million m^3). The river turnover balance is negative and significantly exceeds the atmospheric exchange. Rainfall recharge is only a few percent.

Sensitivity to atmospheric forcing

Charzykowskie Lake is resistant to extreme short-lived atmospheric forcing. This is proven by the reaction of the lake to inflow changes. In the study period, changes in the retention of Charzykowskie Lake were disproportionately small compared to the changes of the water volume taking part in the exchange (Fig. 5). Despite high variability in the conditions of atmospheric recharge, changes in the water level of Charzykowskie Lake in 1961-2015 did not exceed 90 cm, which corresponds to 9% of the total resources stored in the lake. The reaction to increased precipitation was shifted in time. This applies also to the lake's response to a short-term shortage of inflow. As an example one could consider the extremely dry year 2015. At that time, the water level dropped only 20 cm in relation to the average value. A clear limitation of the lake water resources wasn't visible except during the long-term hydrological drought in the 1990s (Fal & Bogdanowicz 2002) (Tab. 2).

Throughout the analysed period, the water surface in the lake did not exceed the threshold values of sensitivity to climate stress (Fig. 3, 4). The morphometric parameters of the lake basin filled with water fluctuated to a small extent (Tab. 2). The shorezone of 1.8 km^2, which represents almost half of the shoreline, but just 13% of the lake area, was exposed during the drought. The length of the shoreline changed – it was 8 km longer with the maximum filling compared to the minimum filling. The changes described did not affect the functional and natural values of the lake.

Discussion and conclusions

Studies have confirmed that the shape of the lake bathymetry is an important factor controlling the lake's hydrological response to changing atmospheric conditions (precipitation, evaporation). The ribbon flow-through lake studied has a low sensitivity to contemporary conditions of water exchange. With a water level amplitude of 90 cm (8 million m^3 of water), the lake's morphological thresholds of sensitivity to changes in retention were not exceeded, and the most realistic degree to which this will occur is the achievement of threshold II.

The following factors contributed to the low sensitivity of the ribbon flow-through lake: (1) the deep lake basin of Charzykowskie Lake; (2) the narrow littoral zone, and (3) the large area of the total catchment (920 km^2), forming a buffer with a reservoir of surface water and groundwater. A large lake catchment mitigates the reaction of the lake to atmospheric conditions (precipitation-evaporation). The water exchange time in the lake is 0.5 years.

Table 2. Comparison of parameters of the lake basin at different water levels in 1961-2015 (the observed and potential levels after exceeding the threshold values)

Water level ordinate [m a.s.l.]	Comments	Water volume [km^3]	Lake surface area [km^2]	Length of shoreline [km]
1961-2015				
120.8	Max	0.15	14.9	43
120.1	Mean	0.14	13.5	34
119.9	Min	0.13	13.1	35
Threshold				
123.5	I	0.29	27.1	81
121.5	II	0.15	15.4	47
118.7	III	0.12	11.8	35

An underground supply is important in maintaining the water resources of the lake. During the long-term drought in the 1990s this supply provided as much as 45 million m^3 of water. By comparison, in order for the average level of water in the lake to decrease below the lowest threshold III, the water retention deficits would have to be 20 million m^3. In practice, this means that disturbance of the water resources in the catchment will affect the condition of Charzykowskie Lake. Shortages of water for municipal purposes already occur in the upper catchment of the Brda River and additional sources of water supply are sought (Hobot et al. 2012).

One must remember that the condition of resources is determined by the time of exposure to adverse conditions. An example of this is the difference in lake response to the long-term water shortages in the 1990s and the dangerous but relatively short episode of meteorological drought that occurred in 2014 and 2015. In the first case, we observed the lowest water levels, while in 2015 the water level fluctuated around the multi-year average.

Contemporary observations only allow for the evaluation of the so-called 'current vulnerability' of the lake being investigated (ICF International 2009). Under such circumstances, the projection of changes in retention as a result of predicted climate change due to global warming is becoming increasingly important (Parry et al. 2007). Examples of this kind of procedure can be found in other regions, e.g. the Neusiedler See (Soja et al. 2013) or Lake Okeechobee (Havens & Steinman 2013). In the case of a flow-through lake with a large catchment this task is not only difficult (interaction of many factors) but it is also subjected to a considerable uncertainty in climate projections (e.g. Rannow et al. 2010; Züger & Knoflacher 2011). Additionally, the assumption that 'contemporary' sensitivity is similar to 'future' (vulnerability) is a major simplification. The assessment of the future responses (vulnerability) of Charzykowskie Lake based on 50 years of experience is justifiable as long as no additional factors occur in the future which would modify the lake's response to climate forcing (Marszelewski & Adamczyk 2004; Johnson & Weaver 2009; Ławniczak et al. 2011). This is confirmed by studies of Polish geomorphologists and palynologists (e.g. Nowaczyk 1994; Kozarski 1995; Gałka 2006; Błaszkiewicz 2007, Szeroczyńska & Zawisza 2011). Contemporary modifying factors can include an anthropogenic steering (for example adding a dam – threshold I).

In water management it is important to determine the threshold conditions under which environmental changes occur (Australian Greenhouse Office 2005). In our case, we used the morphological thresholds of lake sensitivity to changes in retention. They are the equivalent of warning and alarm water levels on rivers. They can be used in an anthropogenic steering of water resources in lakes. The determination of thresholds is not always easy because it depends on the clarity of the relief of the lake basin. In the ribbon lake investigated, the height of the steps dividing the lake ribbon into smaller depressions and the location of the edges limiting the shore zone were taken into account. It should be noted that the accuracy of calculations is determined by the resolution of a bathymetric plan and geodetic data on that part of the lake that has emerged. The study presented a high-resolution model. Unfortunately, detailed mapping of the lakes' shore zones is still insufficient to prepare bathymetric plans of the lakes. In addition, the determination of threshold values for lakes with different morphological structures (less contrast) will require extended hydrobiological research.

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Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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