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The Water Balance in a Dam Reservoir – a Case Study of the Przebędowo Reservoir

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1. Introduction

Extreme weather events, particularly droughts, frequently contribute to disturbances in the natural water balance (Characteristics… 2007). As it was reported by Wibig (2012), the present-day climate warming, in Poland manifested in an increase of temperature in the second half of the 20th century by almost 1°C, has led to a growing risk of water deficits. Climate warming results in an increased potential evaporation, which at practically unchanged precipitation totals causes a reduction of the climatic water balance. According to Radzka (2014), in central and eastern Poland in the months of the vegetation season the frequency of negative climatic water balances is 2-fold greater than the incidence of positive balances. The negative values of this index have been recorded most frequently in the spring months, while the positive balances have been most common in September.

For this reason it continues to be of paramount importance to conduct research on water balances both for entire catchments and reservoirs located in such catchments. However, it needs to be stressed here that at the end of the 20th century very few studies concerned water balances of lakes in Poland; as indicated by Choiński (1995) due to problems in preparing water balances for lake waters such case studies were conducted for only several dozen of lakes in Poland.

Depending on the character of a given reservoir the water balance equations may take more or less complex forms. In relation to dammed reservoirs, which location in the river continuum frequently leads to changes in the previous hydrologic conditions, a reliable characterisation of water balance components is often a complicated process. According to Gruszczyński et al. (2009), one of the most significant changes in the filtration area as a result of damming is related to a unique situation found in the immediate vicinity of the damming structure. This is the site, where hydrogeological conditions have been drastically altered, as it combines the areas with an unchanged drainage base (the region downstream of the damming structure) and areas with a maximum rise of water levels (the region upstream of the damming structure). As it was reported by Traczewska (2012), dammed reservoirs exhibit many characteristics distinguishing them from natural lakes or rivers, and thus they constitute a separate category of surface water bodies.

A reliable determination of individual components of the water balance for a given water body or reservoir not only provides information on its functioning, but also makes it possible to assess its available water capacity. According to Szczykowska and Siemieniuk (2011), water retention in reservoirs, including dammed reservoirs, generally contributes greatly to a marked improvement of the balance of water resources.

In view of the threats related to drought all measures aiming at the determination of the water balances for reservoirs may contribute to the limitation of the adverse effects of droughts.

The aim of this study was to characterise the water balance of a dammed reservoir of Przebędowo in two hydrological years differing in terms of precipitation totals.

2. Material and methods

This study presents the results of investigations conducted in the hydrological years of 2017 and 2018 in the immediate catchment of the Przebędowo reservoir, located in the Wielkopolskie province 25 km north of Poznań in the Murowana Goślina commune (Fig. 1).

According to the physico-geographical regionalisation of Poland (Kondracki 2000) the area of the study with the early post-glacial landscape is located in the Wielkopolska Lake District in the area of the Poznań Warta Gorge (315.52). The total catchment area of the reservoir is approx. 95 km^2, while the direct alimentation area of the lake (catchment direct) covers 1.31 km^2. The areas adjacent to the reservoir are arable lands (cereal crops) composed of fluvial Quaternary (Pleistocene) deposits, while the analysis of layers covered by piezometers showed a predominance of medium sands deposited to a depth of approx. 3 m.

The analysed reservoir was constructed in the valley of the Trojanki river (from 6+915 km to 8+371 km of its course) by the Wielkopolska Land Reclamation and Hydraulic Structure Authority in Poznań and it was commissioned in November 2014. The embankment dam of the reservoir is class IV, it is 334 m in length and 3.30 m in height (Fig. 2).

The reservoir of 1450 m in length and maximum width of 120 m, at the normal pool elevation of 72.50 m a.s.l. has a mean depth of 0.94 m and the pool area of 12.03 ha (Fig. 3, Table 1).

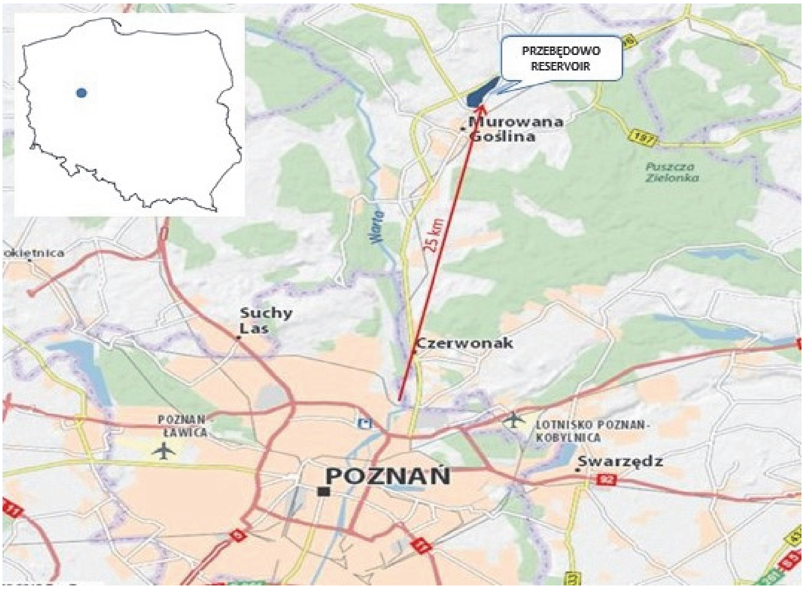

Fig. 1. Location of the Przebędowo reservoir in the Wielkopolska region

Fig. 2. The embankment dam with the spillway-overflow structure (steady level damming) in the Przebędowo reservoir

The shoreline length of the reservoir is 2980 m, shoreline density is 248 m·ha^{-1} and the elongation index is 12. In turn, the flood control capacity derived from the difference between normal and maximum pool level is around 67000 m^3.

Fig. 3. A view of the Przebędowo reservoir (Sojka et al. 2017)

Water levels in the reservoir were measured at the staff gauge installed at the damming structure situated at the reservoir outlet. Additionally, water levels in the reservoir were continuously recorded using a hydrostatic level sensor, which readings were transmitted to a remote telemetry module installed at the spillway tower.

Table 1. Basic morphometric parameters of the Przebędowo reservoir

Item	List	Unit	Value
1	Surface area	ha	12.03
2	Length	m	1450
3	Maximum width	m	120
4	Mean depth	m	0.94
5	Length of shoreline	m	2980
6	Shoreline density	m·ha^{-1}	248
7	Elongation index	–	12
8	Total capacity at normal pool level	m^3	162 350
9	Flood control capacity derived from the difference between normal and maximum pool levels	m^3	67 100

This study was based on measurements of groundwater levels taken at 7 selected wells installed during reservoir construction: P-2 and P-3 in the area adjacent to the reservoir to the west, and wells P-16, P-17, P-18, as well as P-20 and P-21 installed to the east of the reservoir. From May 2016 groundwater levels were measured in additionally installed wells (from 1' to 6') located in the area adjacent to the reservoir at a distance of approx. 10 m from its shore in three representative sections (Fig. 4). Water levels in the years of analysis were measured at 14-day intervals. In turn, weekly water levels in the analysed wells were recreated by calculating mean values from measurements taken every two weeks.

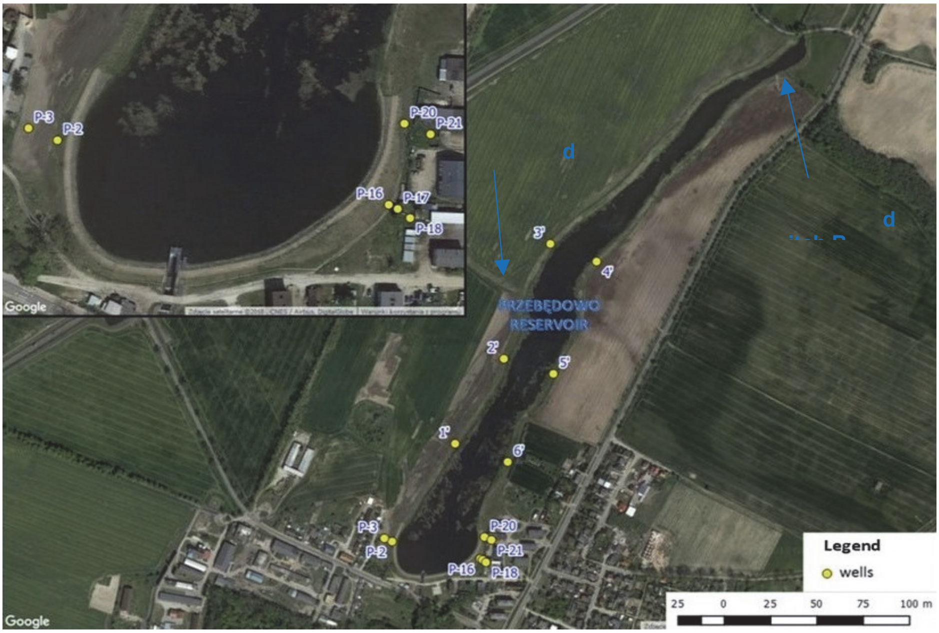

Fig. 4. Location of wells for groundwater level measurements in the area adjacent to the reservoir (source: the authors' study based on Google Earth https://www.google.pl/intl/pl/earth/)

Meteorological conditions in the discussed hydrological years (precipitation and air temperatures), compared to the data from the multiannual period of 2000-2015, were characterised based on the results of measurements recorded at the weather station of the Experimental and Teaching Station of the Forest Arboretum in Zielonka, located approx. 8 km south-east from the reservoir. The weather station is situated in the central part of the Zielonka Forest at 91.00 m a.s.l., at 52°33″00″

northern latitude and 17°06′33″ eastern longitude. Measurements have been recorded there continuously since 1986, while readings are recorded three times a day (Grajewski and Pacholczyk 2011).

Moisture conditions for the analysed hydrological years were characterised according to Kędziora (1995, after Kaczorowska 1962) taking into consideration the criteria given in Table 2.

Table 2. Characteristics of moisture conditions in hydrological years

Type of year	% normal precipitation
Extremely dry	below 50
Very dry	50-74
Dry	75-89
Average	90-110
Wet	111-125
Very wet	126-150
Extremely wet	over 150

In view of the considerable, both half-year and yearly, values of water balance components included in the so-called river water exchange (inflow and surface runoff in the Trojanka watercourse) the water balance of the investigated reservoir was expressed in hm^3 and calculated using the following equation:

$$P + Hd + Hp + Hpp + \Delta R_1 = E + \Delta R_2 + Ho + Hopp + Hw \qquad (1)$$

where: P – precipitation onto the reservoir surface (hm^3), Hd – inflow to the reservoir from the Trojanka watercourse (hm^3), Hp – surface inflow to the reservoir from adjacent areas (hm^3), Hpp – subsurface inflow to the reservoir from adjacent areas (hm^3), ΔR_1 – increase in retention (hm^3) E – evaporation from the reservoir surface (hm^3), ΔR_2 – loss of retention (hm^3), Ho – outflow from the reservoir with the Trojanka watercourse (hm^3), Hopp – subsurface outflow from the reservoir to adjacent areas (hm^3), Hw – uncontrolled underground outflow (hm^3). At the same time, in view of the relatively small fluctuations in water levels within the reservoir, the water balance of the analysed reservoir was assessed in reference to its surface at normal pool level.

In the calculations for the water balance of the analysed reservoir the precipitation level was adjusted by the correction resulting from the formula proposed by Jaworski, recommended for the conditions prevalent in the Wielkopolska region by Kędziora (1995):

$$Ps = 1.034 \cdot Pz + 0.484 \cdot N + 4.0 \qquad (2)$$

where:
Ps – adjusted precipitation (mm),
Pz – precipitation catch (mm),
N – number of days with precipitation in a month.

In turn, precipitation feeding the reservoir was calculated from the dependence:

$$P = Ps \cdot Azb, \tag{3}$$

where:
Ps – adjusted precipitation (mm),
Azb – reservoir surface area (ha).

Values of inflow to the reservoir with the Trojanka watercourse (Hd) and outflows (Ho), as well as surface inflows (Hp) from two drainage ditches (A and B, Fig. 4) feeding the reservoir from the north-west (A) and east (B), were determined based on calculations of flow rates, which in turn were established using water flow velocity measured using a hydrometric current meter (electromagnetic open flow meter FLAT Model 801 by Valeport) with measurements taken once a month. Flows were calculated using characteristic curves plotted based on in-situ measurements.

Values of subsurface inflow to the reservoir from adjacent areas (Hpp) and outflow from the reservoir to adjacent areas (Hopp) were determined using the Darcy formula (Rushton 2003):

$$Q = k \cdot I \cdot O \cdot \Delta h \tag{4}$$

where:
k – hydraulic conductivity ($m \cdot d^{-1}$),
I – hydraulic gradient,
O – length of shoreline (m),
Δh – aquifer thickness (m).

The value of hydraulic conductivity was assumed at $k = 24.704\ m \cdot d^{-1}$, determined as the mean for the values obtained during bore drilling at the installation of piezometers, established using the Hazen method and contained in the documentation from the execution of geotechnical works related to the assembly of piezometers for the small retention reservoir of Przebędowo (2014) and prepared by Geoprogram (W. Andrzejewski, R. Urban) from Bydgoszcz.

The thickness of the aquifer (Δh) participating in the feeding of water to the reservoir from adjacent areas was reversely determined based on the difference between the water level in the reservoir and water levels in the analysed wells (mean value). In turn, the number of days with groundwater being fed by waters stored in the reservoir was determined in the analysed years based on the difference between ordinates of water levels in the reservoir and groundwater levels in the wells included in the analyses.

Monthly evaporation from the reservoir surface was calculated using the formula proposed by Tichomirow (Kędziora 1995):

$$E_1 = d \cdot (15+3 \cdot v) \tag{5}$$

where:
E – monthly evaporation from the water surface (mm),
d – mean monthly humidity deficit (mmHg),
v – mean monthly wind velocity at the anemometer (m/s).

In turn, half-year and yearly values of evaporation were determined from the formula:

$$E=E_1 \cdot Azb \tag{6}$$

where:
E_1 – evaporation from the reservoir surface (mm),
Azb – surface area of the reservoir (m^2).

Increments (ΔR_1) or losses (ΔR_2) of water retention in the reservoir were determined based on changes in water levels recorded at the staff gauge installed at the damming structure. In turn, the value of uncontrolled underground outflow (Hw) was determined as the compliment to the water balance equation.

Data on recorded water levels in the discussed facility were used as kindly provided at the permission of the Director of the former Wielkopolska Land Reclamation and Hydraulic Structure Authority in Poznań (presently the State Water Holding Polish Waters; Regional Water Management Authority in Poznań).

3. Results and discussion

Wielkopolska is a region, in which the vegetation period is one of the longest in Poland, starting the earliest in western Wielkopolska, where it begins around 28 March. In the South Wielkopolska Lowland the vegetation period lasts approx. 228 days, whereas at its northern boundaries it is only 216 days. Mean annual precipitation totals are 500-550 mm, while in the Gniezno Lake District and in the southern parts of the Kujawy region they are by 50-100 mm lower. The precipitation deficit is observed particularly in the eastern part of the province. Precipitation is highly irregular and differences in precipitation totals in individual years may be as high as 250%. The distribution of precipitation during the year or the vegetation period is also far from uniform. More precipitation in the summer period is recorded in the vicinity of water bodies, reservoirs and river valleys, which are located in the paths of storms. Mean annual temperature for the Wielkopolska region is approx. 8.2°C, in the north it drops to 7.6°C, while in the southern and western edges it reaches 8.5°C. Extreme temperatures in the summer period reach +38°C, while during the harshest winters they drop to almost –30°C (Program… 2016, after Bąk 2003).

The hydrological year of 2017 was very wet, since precipitation total in that year exceeded the multiannual mean by as much as 244 mm, at air temperatures close to the mean (Fig. 5).

The winter half-year in that year was average, with precipitation total of 211 mm, by 18 mm lower than the mean. In turn, the summer half-year was extremely wet, as precipitation total in that half-year was 593 mm and it was higher than the multiannual mean by 263 mm, at air temperature exceeding the mean by 0.2°C.

In turn, the second analysed hydrological year (2018) was a very dry year, in which precipitation total was equivalent to as little as 65% normal precipitation and it was lower than that value by 196 mm, at air temperature higher by 1.1°C compared to the mean. Both the winter and summer half-years of that year were very dry, with precipitation totals lower than the means by 79 mm and 115 mm, at air temperatures higher than the means by 0.4°C and as much as 1.6°C, respectively.

Analyses of mean monthly water levels in the investigated reservoir indicate that in the month preceding the winter half-year of 2017 (November) the mean water level was 317 cm (Fig. 6). Precipitation total of 78 mm, which was observed in November and in December, caused a rise in water levels. Mean monthly water level in the reservoir in December was 328 cm and at the same time it was the highest mean value in the discussed half-year. From January to the end of the analysed half-year a lowering of water levels was recorded in the reservoir.

The lowest mean water level was recorded in April and it amounted to 308 cm, being by as little as 7 cm higher than the level corresponding to the normal pool level. A considerable effect on such a situation was exerted by higher air temperatures in March and April and evaporation from the reservoir surface, which jointly in those months amounted to 113 mm.

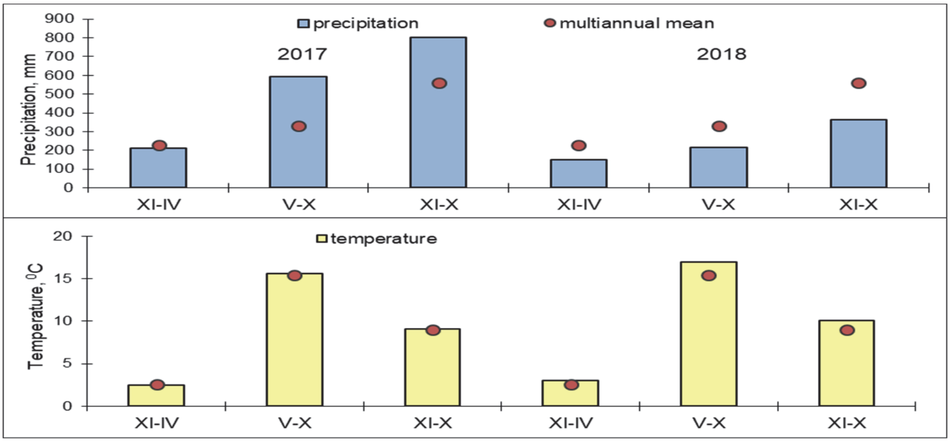

Fig. 5. Half-year and yearly precipitation (P) and average air temperatures (t) in 2017 and 2018 hydrological years, and their deviations from averages of the multiyear period of 2000-2015

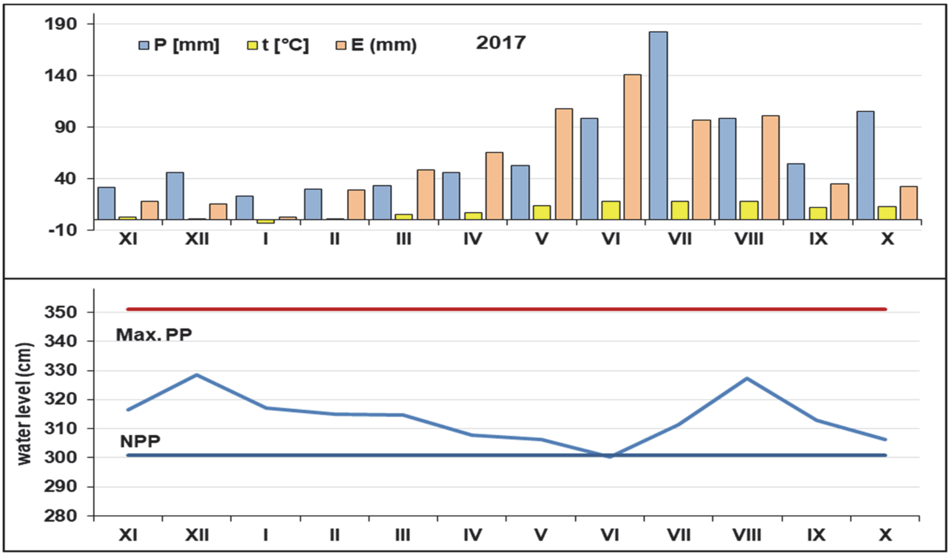

Fig. 6. Mean monthly water levels (cm) in the Przebędowo reservoir and levels corresponding to normal (NPP) and maximum pool levels (Max PP) depending on mean monthly precipitation totals (P) and mean monthly air temperatures (t) as well as monthly evaporation from the reservoir surface (E) in the hydrological year of 2017

In the beginning of the summer half-year (May) of 2017 the mean water level in the analysed reservoir was 306 cm. Higher mean monthly air temperatures observed in May and June (13.8°C and 17.8°C, respectively), as well as high evaporation from the reservoir recorded in those months (jointly 173 mm) contributed to a further lowering of water levels. The mean water level in the reservoir in June was 300 cm and it was the lowest mean level both in the discussed summer half-year and in the entire hydrological year of 2017. In July and August water levels in the reservoir were observed to raise, while their mean values in those months were 311 cm and 327 cm, respectively. A considerable effect on this situation, despite higher air temperatures and evaporation from the reservoir surface, was found for precipitation total of 282 mm, recorded in those months. Results obtained for those months were consistent e.g. with the studies by Błażyca and Rzętała (2013) concerning analyses of changes in water levels in the Pławniowice reservoir, since those authors stressed that maximum water levels were observed in the summer half-year, typically at the turn of July and August following precipitation with high daily totals.

From August to the end of the discussed summer half-year water levels in the reservoir were lowering. The mean water level in September was 313 cm, while in October it was 306 cm. However, it needs to be stressed here that the lowering of the water levels towards the end of the discussed half-year was not directly connected with the course of weather conditions, since precipitation total for September and October was 161 mm, while total evaporation for those months was 67 mm. The values of evaporation calculated for those months were consistent with the results of calculations presented by Górski et al. (2009) in their analysis of the water balance for Lake Czerniakowskie and with the results of direct measurements obtained e.g. for Lake Raduńskie Górne by Wereski et al. (2017). As it was reported by Waligórski et al. (2019), the lowering of water levels in the Przebędowo reservoir was caused by a considerable effect of the anthropogenic factor, related to the opening of bottom gates towards the end of August, in a situation when higher daily precipitation totals and the vegetation debris jamming the damming structure posed a risk of crest overflow spill and flooding of buildings located nearby.

In the winter half-year of the second analysed year of the analyses (2018) the mean water level in the reservoir in November was 305 cm (Fig. 7). In the period from November to February water levels were lowering and during that period they remained below the normal pool level.

Similarly as in the previous analysed year of the study, the marked lowering of water levels in February, when the mean water level was 277 cm and it was lower than normal pool level by 24 cm, was not caused by the weather conditions, but by anthropopressure. In the course of maintenance works performed in that month due to negligence the bottom gates were left partly open, which resulted in an uncontrolled outflow of water from the reservoir and a lowering of water levels. As it was reported by Mioduszewski and Okruszko (2016), the hydrological functions of this reservoir may be considerably influenced also by its operation. Until the end of the discussed winter half-year the water levels in the reservoir were raising as a result of the bottom gates being completely shut and the progressing reservoir filling. In April the mean water level in the reservoir was 302 cm and it was similar to that corresponding to the normal pool level.

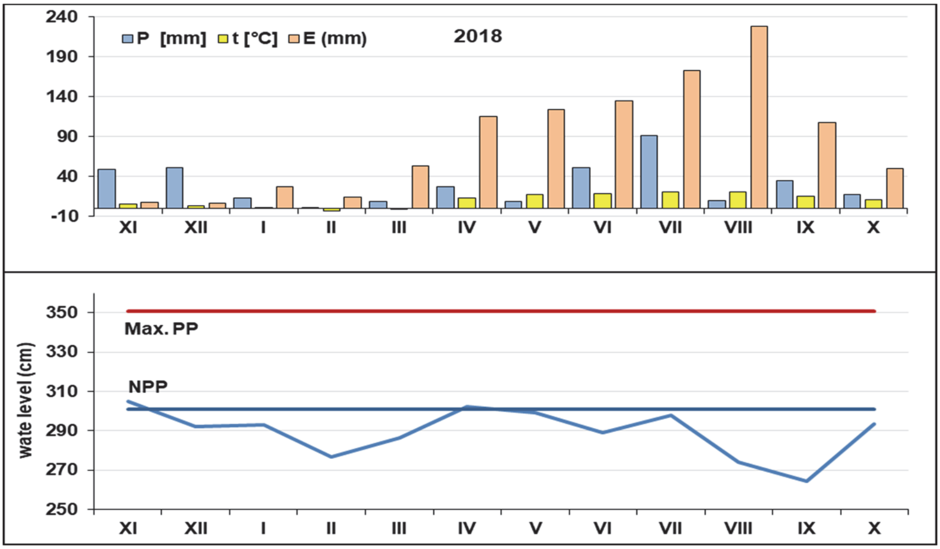

Fig. 7. Mean monthly water levels (cm) in the Przebędowo reservoir and levels corresponding to normal (NPP) and maximum pool levels (Max PP) in view of mean monthly precipitation totals (P) and mean monthly air temperatures (t) and monthly evaporation from the reservoir surface (E) in the hydrological year of 2018

From the beginning of the summer half-year the water levels in the discussed reservoir were falling and in June the mean water level was 289 cm. To a considerable extent this situation was the result of the weather conditions, particularly low precipitation total in May (9 mm) and high evaporation from the reservoir, which total joint value for May and June was as high as 259 mm. A slight increase in water levels in the reservoir was recorded in July due to precipitation total for that month amounting to 92 mm, when the mean water level reached 298 cm.

At the turn of August and September a considerable lowering of water levels was caused to a considerable extent by adverse weather conditions, particularly low precipitation totals in that month, at higher air temperatures and very high evaporation from the reservoir, which jointly amounted to as much as 336 mm. The mean water level in the analysed reservoir in September was 265 cm and it was lowest both in the discussed summer half-year and over the entire hydrological year of 2018.

Towards the end of the discussed half-year water levels were found to increase in the reservoir and in October the mean level was 293 cm. However, throughout the entire analysed summer half-year, which in terms of precipitation was very dry, the mean water levels in the reservoir remained below the level corresponding to the normal pool level (301 cm).

Analysis of the water balance for the Przebędowo reservoir indicates that in the winter half-year of the first year of the study the highest share in terms of increments was recorded for the inflow to the reservoir by the Trojanka watercourse, which in the discussed half-year was 12.9 hm^3 (Table 3).

Table 3. Components of water balances of the Przebędowo reservoir (hm^3) in the winter (XI-IV) and summer (V-X) hydrological half-years of 2017 and 2018

Increments (+) and losses of water (-)	Water balance components	Hydrological half-years			
		2017		2018	
		XI-IV	V-X	XI-IV	V-X
(+)	P	0.03	0.08	0.027	0.032
	Hd	12.9	10.7	5.16	3.59
	Hp	0.165	0.047	0.0025	-
	Hpp	0.0015	0.0002	–	–
	ΔR_1	–	0.011	–	0.004
(-)	E	0.02	0.06	0.03	0.098
	ΔR_2	0.0048	–	0.036	–
	Ho	10.0	9.06	3.75	2.70
	Hopp	0.56	0.55	0.81	0.78
	Hw	2.51	1.16	0.55	0.046

According to Rzętała (2008), when analysing water balances of anthropogenic reservoirs, including dammed reservoirs, in terms of the type of water feeding and artificial control of water circulation, the results of calculations should be expressed in hm^3 rather than in millimeters, as it is the typical practice in geographical studies.

To a much lesser extent the increments in water resources in that half-year were determined by the inflow to the reservoir from adjacent areas, which was 0.165 hm^3.

In turn, to the lowest extent the increments were determined by precipitation falling on the surface of the reservoir and by the subsurface inflow to the reservoir from adjacent areas, which in the discussed half-year amounted to 0.03 hm^3 and 0.0015 hm^3, respectively. In terms of the water losses the highest share in the water balance equation was found for the outflow from the reservoir with the watercourse, amounting to 10.0 hm^3. Uncontrolled underground outflow determined as the complement in the balance equation was 2.51 hm^3. As reported by Rösler et al. (2007), when characterising the water balance of Lake Sława the greatest methodological problems were caused by water exchange in the underground drainage zone, frequently leading to a situation when the parameters of underground exchange are typically calculated from the water balance difference. The underground outflow is often problematic; as reported by Lange (1993), currently available research results indicate a considerable predominance of feeding by the underground outflow. Some hydrologists even claim that the underground loss of water is rather unlikely due to the strong bottom sealing of lake basins by impermeable sediments. Previously cited Rösler et al. (2007) reported that colmatation, i.e. silting and sealing of lake basic bottoms by sediments, takes place and plays a significant role in blocking the underground outflow. However, according to those authors particularly in flow-through lakes in the outflow zone sediments may be washed away and wide marginal stream valley filled with permeable deposits (sands, gravel) form the so-called underground outflow gateways. Similar observations were reported by Wojtuszewska (2007) and Dąbska and Popielski (2020), in whose opinion operation of dammed reservoirs is frequently connected with hydrogeological problems, the most frequent of which include e.g. excessive filtration to the substrate and within the dam abutment zone. In the latter case this is frequently caused by quick sands or the so-called piping.

In the analysed half-year the losses in the water balance were to a lesser extent determined by subsurface outflow from the reservoir to adjacent areas, amounting to 0.56 hm^3. In turn, the smallest share was recorded for evaporation from the reservoir, which was 0.02 hm^3, and water storage loss in the reservoir, which amounted to 0.0048 hm^3. In the summer half-year of the discussed hydrological year of 2017, similarly as it was in the winter half-year, a major factor in the water balance of the reservoir in terms of increments was related to the inflow by the watercourse, which amounted to 10.7 hm^3. To a much lesser extent the increments were determined by surface inflow from adjacent areas, which reached 0.047 hm^3. In turn, precipitation falling on the reservoir surface in the discussed half-year amounted to 0.08 hm^3, while the increment in retention was 0.011 hm^3. The lowest share in the water increments in that half-year was observed for subsurface inflow to the reservoir from adjacent areas, being as low as 0.0002 hm^3. In relation to water losses the greatest share in the balance equation in that half-year was recorded for the outflow from the reservoir through the watercourse, which was 9.06 hm^3. Uncontrolled underground outflow and subsurface outflow from the reservoir to adjacent areas amounted to 1.16 hm^3 and 0.55 hm^3, respectively. In turn, water losses related to evaporation from the reservoir amounted to 0.06 hm^3.

In the second analysed hydrological year of 2018, which in terms of precipitation was very dry, both in the winter half-year (XI-IV) and the summer half-year (V-X), the highest share in the water balance of the reservoir in the case of increments was recorded for the Trojanka inflow, amounting to 5.16 hm^3 and 3.59 hm^3, respectively (Table 3). However, it needs to be observed here that these values in relation to inflows from the previous year were much smaller. In the winter half-year of 2018 the difference was 7.74 hm^3, while in the summer half-year it was 7.11 hm^3. To a much lesser degree the increments in the discussed half-years were determined by precipitation falling on the reservoir surface, which in the winter half-year was 0.027 hm^3, while in the summer half-year it reached 0.032 hm^3. The increments to a slight extent were also determined by surface inflow from adjacent areas (in ditches A and B), which was observed only in the winter half-year and amounted to 0.0025 hm^3, as well as the increment of water storage amounting to 0.004 hm^3, reported in the summer half-year. It needs to be stressed here that both in the winter and summer half-years of the discussed hydrological year the reservoir was not fed by groundwaters from adjacent areas (Hpp). In turn, in terms of water losses the highest share in the water balance equation for the analysed reservoir was found for the outflow from the reservoir through the watercourse (Ho), which in the winter half-year amounted to 3.75 hm^3, while in the summer half-year it reached 2.70 hm^3. However, they were much lower values (by approx. 6 hm^3) in comparison to outflows in 2017, being a wet year in terms of precipitation. A significant share in the losses was also found for subsurface outflow from the reservoir to adjacent areas (Hopp), which suggests that in the discussed hydrological year the reservoir played only the feeding function. In the winter half-year the outflow amounted to 0.81 hm^3, while in the summer half-year it was 0.78 hm^3. It may be stated here the analysed Przebędowo reservoir fully served a major function ascribed to retention reservoirs, since as it was reported by Humnicki (2010) and Jaguś et al. (2010) the main role of such reservoirs is to store water in periods of its excess to be subsequently used during dry spells, e.g. by feeding groundwaters in adjacent areas.

Losses in the water balance equation for the reservoir in the discussed hydrological year were to a lesser extent affected by uncontrolled underground outflow, in the winter half-year amounting to 0.55 hm^3, while in the summer half-year it was 0.046 hm^3. In turn, the least important effect on water losses was observed for evaporation from the reservoir surface, which in the winter half-year amounted to 0.03 hm^3, while in the summer half-year it was 0.098 hm^3, similarly as it was for storage losses, which in the winter half-year amounted to 0.036 hm^3.

Analyses of the percentage share of individual components of the water balance for the Przebędowo dammed reservoir over the entire period of the discussed hydrological years show that in the hydrological year of 2017 increments were determined to the greatest extent by inflow to the reservoir through the Trojanka watercourse (Hd), accounting for 49.3% (Fig. 8).

To a lesser extent the water increments were influenced by the surface inflow from adjacent areas (Hp), which constituted 0.44%, and precipitation (P) falling on the reservoir surface (0.23%). In turn, the lowest shares in the water balance equation were found for the increment in water storage (ΔR_1) and subsurface inflow to the reservoir from adjacent areas (Hpp), which accounted for as little as 0.023% and 0.004%. In terms of losses the greatest share in the water balance for the discussed year was observed for surface outflow from the reservoir (Ho), which accounted for 39.8%, and for uncontrolled underground outflow (Hw) constituting 7.7%. Losses were determined to a lesser extent by subsurface outflows from the reservoir to adjacent areas (Hopp) and evaporation from the reservoir (E), which percentage shares in the water balance were 2.3% and 0.17%, respectively. In turn, the lowest share (0.01%) was found for the water storage losses (ΔR_2). In the second analysed hydrological year of 2018, similarly as in 2017, a crucial share in increments was recorded for the watercourse inflow to the reservoir, which accounted to 49.7%. In turn, the percentage shares of the other water balance components determining the increments, such as precipitation falling on the reservoir surface, surface inflow from adjacent areas and the increment in water storage, were slight. In the case of water losses the greatest role in that year in the water balance was played by the outflow from the reservoir through the watercourse, accounting for 36.6%. A relatively high share was found for the subsurface outflow from the reservoir to adjacent areas (9%) and uncontrolled underground outflow (3.4%). To a lesser extent the losses were determined by evaporation from the reservoir (0.73%) and water storage losses (0.2%).

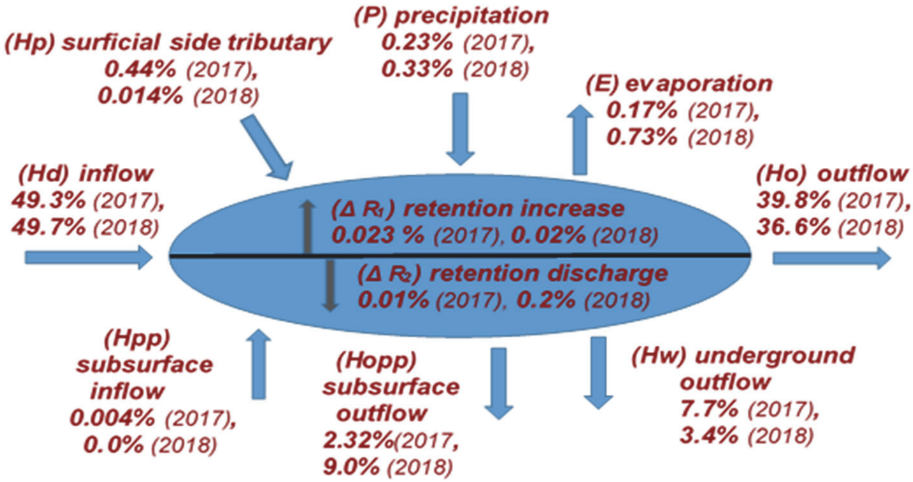

Fig. 8. Graphic representation of water balance components (%) for the Przebędowo reservoir in the hydrological years 2017 and 2018

Results recorded in the discussed years are consistent with e.g. those presented by Rzętała (2000), concerning water balance characteristics of the Dzierżno Duże reservoir, as that author stressed the greatest effect on the water balance exerted by inflow and surface outflow. In turn, precipitation in the case of increments and evaporation from the reservoir in the case of losses played a marginal role in the water balance. Analysis of the water balance components for the Przebędowo reservoir confirmed also the results of a study by Fac-Benedy (2013) concerning hydrological characterisitcs of Lake Drużno, in which the author stressed that the primary elements in the water balance of flow-through lakes are connected with inflow and surface outflow, since the vertical water exchange is less intensive than the horizontal exchange and it does not fundamentally alter the general balance structure. Similar conclusions were also drawn by Kropka and Jagliński (2015) when analysing the water balance for the underground catchment of the Kuźnica Warężyńska reservoir (Kotlina Dąbrowska). Those authors reported the greatest share in the water balance in the case of increments for surface inflow, while in the case of losses surface outflow from the reservoir was definitely dominant.

4. Conclusions

1. Obtained research results showed that in the hydrological year of 2017, which in terms of precipitation was very wet, mean water levels in the reservoir remained between normal and maximum pool levels. The highest mean water level in the winter half-year of that year was recorded in December (328 cm), while in the summer half-year it was in August (327 cm). In turn, for a greater part of the very dry hydrological year of 2018 mean water levels in the reservoir remained below the normal pool level. The lowest mean level was observed in that year in September (265 cm), which to a considerable extent was determined, among other things, by very high evaporation from the reservoir surface (228 mm), which was recorded in August.
2. The conducted analyses confirmed that apart from the weather conditions such as precipitation, air temperatures and evaporation from the reservoir a considerable role for the fluctuations in water levels in the reservoir was played by the anthropogenic factor. It was particularly related with the manner of reservoir operation frequently characteristic to dammed reservoirs and with the artificial control of water circulation.
3. The performed analysis of the water balance for the Przebędowo reservoir showed that in the winter half-years of the analysed hydrological years of 2017 and 2018 the dominant factor in the case of increments was connected with inflow to the reservoir in the Trojanka watercourse, amounting to 12.9 hm^3 and 5.16 hm^3, respectively. To a much lesser extent the increments of water in those half-years were determined by the inflow to the reservoir from adjacent areas and by precipitation. In the case of losses the greatest share in the water balance was observed in the discussed half-years for outflow from the reservoir through the watercourse, which amounted to 10.0 hm^3 and 3.75 hm^3. To a lesser extent losses were determined by the uncontrolled underground outflow and subsurface inflow to the reservoir from adjacent areas. In turn, evaporation from the reservoir surface and water storage losses determined losses only slightly.
4. In the summer half-years the increments in the water balance to the greatest extent were determined by inflows to the reservoir through the watercourse, which amounted to 10.7 hm^3 (2017) and 3.59 hm^3 (2018), while in the case of losses it was outflows from the reservoir amounting to 9.06 hm^3 and 2.7 hm^3. In turn, a lesser role was played in the case of losses by outflow from the reservoir to adjacent areas, which in the discussed half-years was comparable and amounted to a mean 0.66 hm^3.

5. Throughout the entire period of the analysed hydrological years of 2017 and 2018 the greatest share in the water balance for the Przebędowo reservoir was recorded for the components related with the horizontal water exchange. Inflows to the reservoir through the Trojanka watercourse and outflows constituted mean 49% and 38%, respectively. In the dry hydrological year of 2018 a significant share, in comparison to the other components, in the water balance was also found for the subsurface outflows from the reservoir to adjacent areas, accounting for 9%. In contrast, no major share in the water balance was found for the factors related with the vertical water exchange, characteristic of reservoirs having no outlets, such as precipitation and evaporation from the reservoir surface.

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Abstract

This study presents the results of investigations conducted in the hydrological years of 2017 and 2018 in the immediate catchment of the Przebędowo reservoir, located in the Wielkopolskie province 25 km north of Poznań in the Murowana Goślina commune. The immediate catchment of the reservoir is approx. 95 km^2 in area, while the direct recharge area of the lake (immediate catchment) covers 1.31 km^2. The areas adjacent to the reservoir are arable lands composed of fluvial Quaternary (Pleistocene) deposits, while the analysis of layers covered by piezometers showed a predominance of medium sands deposited to a depth of approx. 3 m. The analysed reservoir was constructed in the valley of the Trojanki river (from 6+915 km to 8+371 km of its course) by the Wielkopolska Land Reclamation and Hydraulic Structure Authority in Poznań and it was commissioned in November 2014. The embankment dam of the reservoir is class IV, it is 334 m in length and 3.30 m in height. The reservoir of 1450 m in length and maximum width of 120 m, at the normal pool elevation of 72.50 m a.s.l. has a mean depth of 0.94 m and the pool area of 12.03 ha. The shoreline length of the reservoir is 2980 m, shoreline density is 248 m·ha^{-1} and the elongation index is 12. In turn, the flood control capacity derived from the difference between normal and maximum pool level is around 67 000 m^3.

The conducted analyses confirmed that apart from the weather conditions such as precipitation, air temperatures and evaporation from the reservoir a considerable role for the fluctuations in water levels in the reservoir was played by the anthropogenic factor. It was particularly related with the manner of reservoir operation frequently characteristic to dammed reservoirs and with the artificial control of water circulation.

Analysis of the water balance for the Przebędowo reservoir showed that in the winter half-years of the analysed hydrological years of 2017 and 2018 the dominant factor in the case of increments was connected with inflow to the reservoir in the Trojanka watercourse, amounting to 12.9 hm^3 and 5.16 hm^3, respectively. To a much lesser extent the increments of water in those half-years were determined by the inflow to the reservoir from adjacent areas and by precipitation. In the case of losses the greatest share in the water balance was observed in the discussed half-years for outflow from the reservoir through the watercourse, which amounted to 10.0 hm^3 and 3.75 hm^3. To a lesser extent losses were determined by the uncontrolled underground outflow and subsurface inflow to the reservoir from adjacent areas. In turn, evaporation from the reservoir surface and water storage losses determined losses only slightly. Whereas in the summer half-years the increments in the water balance to the greatest extent were determined by inflows to the reservoir through the watercourse, which amounted to 10.7 hm^3 (2017) and 3.59 hm^3 (2018), while in the case of losses it was outflows from the reservoir amounting to 9.06 hm^3 and 2.7 hm^3. In turn, a lesser role was played in the case of losses by outflow from the reservoir to adjacent areas, which in the discussed half-years was comparable and amounted to a mean 0.66 hm^3.

Throughout the entire period of the analysed hydrological years of 2017 and 2018 the greatest share in the water balance for the Przebędowo reservoir was recorded for the components related with the horizontal water exchange. Inflows to the reservoir through the Trojanka watercourse and outflows constituted mean 49% and 38%, respectively. In the dry hydrological year of 2018 a significant share, in comparison to the other components, in the water balance was also found for the subsurface outflows from the reservoir to adjacent areas, accounting for 9%. In contrast, no major share in the water balance was found for the factors related with the vertical water exchange, characteristic of reservoirs having no outlets, such as precipitation and evaporation from the reservoir surface.

Keywords:
small-scale water retention, dammed reservoirs, water balances

Bilans wodny zbiornika zaporowego na przykładzie obiektu Przebędowo

Streszczenie

W pracy przedstawiono wyniki badań przeprowadzonych w latach hydrologicznych 2017 i 2018 w zlewni bezpośredniej zbiornika Przebędowo, zlokalizowanego w województwie wielkopolskim, 25 km na północ od Poznania w gminie Murowana Goślina. Powierzchnia zlewni całkowitej zbiornika wynosi około 95 km^2, natomiast obszar bezpośredniej alimentacji jeziora (zlewnia bezpośrednia) zajmuje powierzchnię 1,31 km^2.

Tereny przyległe do zbiornika to grunty orne zbudowane z osadów czwartorzędowych (plejstocen) fluwialnych, a analiza warstw objętych piezometrami wykazała przewagę piasków średnich zalegających do głębokości około 3 m. Analizowany zbiornik został wykonany w dolinie rzeki Trojanki (od km 6+915 do km 8+371 jej biegu), przez Wielkopolski Zarząd Melioracji i Urządzeń Wodnych w Poznaniu i został oddany do eksploatacji w listopadzie 2014 roku. Ziemna zapora czołowa na zbiorniku jest klasy IV, jej długość wynosi 334 m, przy wysokości 3,30 m. Zbiornik o długości 1450 m i szerokości maksymalnej 120 m, przy normalnym poziomie piętrzenia (NPP) wynoszącym 72,50 m n.p.m. ma średnią głębokość 0,94 m i powierzchnię zalewu 12,03 ha. Długość linii brzegowej omawianego zbiornika wynosi 2980 m, jej rozwinięcie kształtuje się na poziomie 248 $m \cdot ha^{-1}$ a wskaźnik wydłużenia wynosi 12. Natomiast rezerwa powodziowa stanowiąca różnicę pomiędzy NPP, a Max. PP osiąga wartość na poziomie około 67000 m^3.

Przeprowadzone badania potwierdziły, że poza czynnikami meteorologicznymi takimi jak opady atmosferyczne, temperatury powietrza oraz parowanie z powierzchni zbiornika duży wpływ na kształtowanie się stanów wody w zbiorniku miał również czynnik antropogeniczny. W szczególności związany z, często charakterystycznym dla zbiorników zaporowych, sposobem eksploatacji zbiornika i sztucznym sterowaniem obiegiem wody.

Analiza bilansu wodnego zbiornika Przebędowo wykazała, że w półroczach zimowych analizowanych lat hydrologicznych 2017 i 2018 czynnikami wiodącymi po stronie przychodów były dopływy do zbiornika ciekiem Trojanka wynoszące odpowiednio 12,9 hm^3 i 5,16 hm^3. W znacznie mniejszym stopniu o przychodach wody w tych półroczach decydowały dopływ do zbiornika z terenów przyległych oraz opad atmosferyczny. Po stronie rozchodów największy udział w równaniu bilansowym miał, w omawianych półroczach odpływ ze zbiornika ciekiem, który wyniósł 10,0 hm^3 i 3,75 hm^3. W mniejszym stopniu o rozchodach decydował niekontrolowany odpływ wgłębny oraz dopływ podpowierzchniowy do zbiornika z terenów przyległych. Parowanie z powierzchni zbiornika oraz ubytki retencji decydowały o rozchodach w sposób nieznaczny. Natomiast w półroczach letnich o przychodach w równaniu bilansowym w największym stopniu również decydowały dopływy do zbiornika ciekiem, które wyniosły 10,7 hm^3 (2017) oraz 3,59 hm^3 (2018), a postronnie ubytków odpływy ze zbiornika kształtujące się na poziomie odpowiednio 9,06 hm^3 oraz 2,7 hm^3. Natomiast w mniejszym stopniu o rozchodach decydował odpływ ze zbiornika do przyległych terenów, który w omawianych półroczach był zbliżony i kształtował się na średnim poziomie 0,66 hm^3.

W skali całych analizowanych lat hydrologicznych największy udział w bilansie wodnym zbiornika Przebędowo miały składowe związane z poziomą wymianą wody. Dopływy do zbiornika ciekiem Trojanka oraz odpływy stanowiły średnio około 49% i 38%. W suchym pod względem opadów roku hydrologicznym 2018 istotny, w porównaniu do pozostałych składowych, udział w bilansie miał również odpływ podpowierzchniowy ze zbiornika do przyległych terenów stanowiąc 9%. Natomiast nie stwierdzono w bilansie wodnym znacznego udziału czynników związanych z wymianą pionową wody, charakterystycznego dla zbiorników bezodpływowych, takich jak opady atmosferyczne oraz parowanie z powierzchni zbiornika.

Słowa kluczowe:
mała retencja, zbiorniki zaporowe, bilans wodny