Water balance of selected floodplain lake basins in the Middle Bug River valley

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Abstract. This study is the first attempt in the literature on the subject of comparing water balance components for floodplain lake basins, depending on the type of a lake connection to the parent river. Research was carried out in the Bug River valley in 2007–2011 water years. Four types of connections were distinguished in the area under study. Simple water balance equation could only be used with regard to the lakes connected to the main river via the upstream crevasses. Detailed and individual water balance equations were developed with reference to the other types of lakes. Water gains and losses varied significantly in the lakes under study. Values of horizontal water balance components (inflow and outflow) of the floodplain lake in Wola Uhruska considerably prevailed over the vertical ones (precipitation and evaporation). Inflow of the Bug River waters was diverse during the time period under study and amounted from 600 000 to 2 200 000 $m^3 yr^{-1}$. Volumes of precipitation and evaporation were rather stable and amounted to approx. 30 000 $m^3 yr^{-1}$. The lowest disparity between horizontal and vertical water balance components was observed in the inter-levee lake. Both upstream inflow of rivers water and outflow from the lake (ranged from 0 in 2008 to 35 000 $m^3 yr^{-1}$ in 2009) were usually an order of magnitude higher than precipitation and evaporation from the lake surface (700–800 $m^3 yr^{-1}$). Study showed that the values and the proportion between aforementioned vertical and horizontal water balance elements were determined by the type of a lake connection to the Bug River. Storage volume showed no relationship to the type of connection, but resulted from individual features of the lakes (location within the valley, precipitation and evaporation volume, difference between water inflow and outflow).

1 Introduction

Floodplain lakes (FPLs) constitute a very large group of global water bodies. The existing classifications of floodplain lakes are mostly based on their origins (Hutchinson, 1957; Drago, 1976; Chmiel et al., 2003). Drago (1989) listed the following among the most common types of FPLs: obstruction ponds, levee ponds, lateral expansion ponds, inter-bar ponds, overflow ponds, annexation ponds and swamps. Dawidek and Ferencz (2012) (after Chmiel et al., 2003) distinguished the following genetic types of lakes for temperate zones (based on the example of Poland): oxbow, inter-levee, anastomotic and avulsion lakes. The hydrological (the degree of filling of the basin) and ecological state mostly depends on the type of connections that the lake has to the parent river, as well as on the frequency of flooding (Tockner et al., 2000; Amoros and Bornette, 2002; Henry and Costa, 2003).

Hamilton and Lewis (1987) and Garcia de Emiliani (1997) distinguished four functional phases on the basis of the seasonal fluctuations of the hydrochemical parameters of a basin: filling, flow-through, drainage and isolation. Their approach is directly related to the flood pulse concept (Junk et al., 1989; Junk, 1997). Tockner et al. (1999) identified three types of hydrological connectivity of floodplain lakes with the river Danube: (a) disconnection, (b) seepage inflow and downstream surface connections; and (c) upstream and downstream surface connections. As for Polish floodplain lakes, four types have been recognised based on their connections to the main river: (a) confluent – which are supplied from the direction of the headwater and whose outflow is in the opposite direction (Fig. 1a); (b) contrafluent – which are both supplied and drained via the same downstream channel
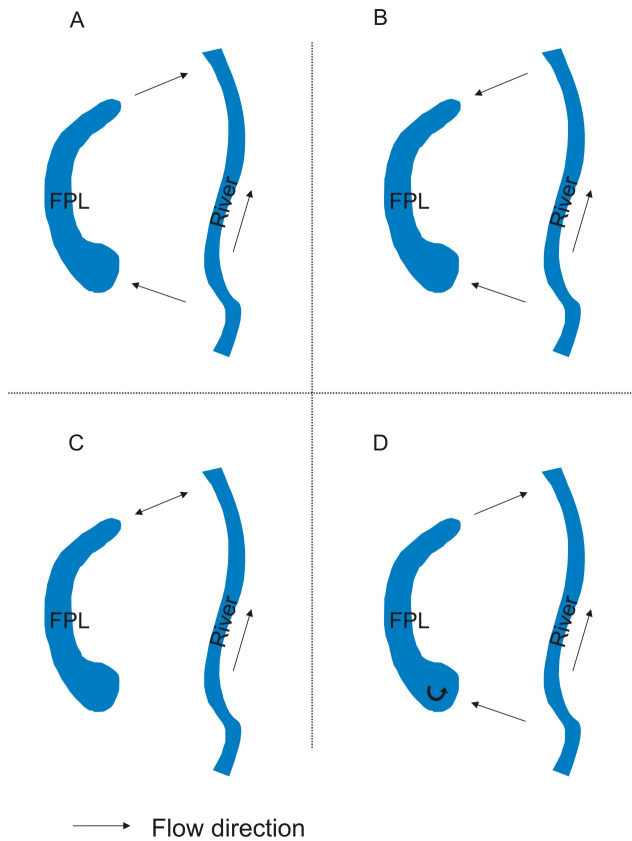
Fig. 1. Types of possible connections of the floodplain lakes to the Bug River in the present study: **(A)** confluent inflow, **(B)** contrafluent inflow, **(C)** contrafluent–confluent inflow, and **(D)** confluent–profundal inflow.

(Lesack, 1993; Bonnet et al., 2008; Sriwongsitanon et al., 2009; Alsdorf et al., 2010) can be presented as follows:

$$(P - E) + (I - O) \pm \mathrm{d}S/\mathrm{d}t = 0, \tag{1}$$

where P denotes precipitation on the water surface, E evaporation from lake's surface, I inflow to the lake basin, O outflow, and $\mathrm{d}S/\mathrm{d}t$ changes in lake storage

Profundal recharge is a constant and periodically high input of groundwater. This also significantly hinders the assessment of the hydrological balance for FPL basins. This form of lake basin supply clearly becomes more prevalent in the narrow sections of a floodplain which is located at the foot of an older terrace. Even a slight increase in groundwater hydraulic gradients in such areas facilitates inflow to floodplain lake basins which, due to their depth, act as a local drainage base for the water-bearing zone. The role of profundal inflow rises in the period of limnophase, as it is the only form of basin supply during without rainfall periods. The possibility of the occurrence of both potamophase and limnophase in the same month is an important event when one assesses lake water balance while maintaining the structure of monthly equations. Higher values of horizontal components of water balance are observed during potamophase period, while vertical components prevail during limnophase period.

Due to the natural character of the valley of the Bug River, the modifications of water flow result from the change of cross-sectional geometry, which is a consequence of erosion or the deposition of mineral and organic sediments in crevasses both supplying and draining the lake. The damming up of water due to the overgrowing of crevasses in summer and the formation of ice cover in winter may also hinder hydrometric measurements. The height and location of beaver dams also has a significant impact on the character of lake water runoff (in terms of quantity and time), which influences the water exchange rate and changes the water storage of a lake.

This paper aims to calculate and analyse the water balance elements of floodplain lake basins, depending on the type of the connection between the lake and the parent river (confluent, contrafluent, contrafluent–confluent or profundal). The small capacity of the lake basins referenced in this study, originating from fluvial activity of the river whose average flow rate amounts to circa $50 \, \mathrm{m}^3 \, \mathrm{s}^{-1}$, allows for the hypothesis that horizontal (fluvial inflow and outflow) water balance elements dominate in the water balance of the lakes. We hypothesised that the type of connection between a floodplain lake and its parent river determines the relationship between the vertical (precipitation, evaporation) and the horizontal water balance elements. We also assumed that the difference between fluvial inflow and drainage, not the precipitation volume, determines the quantity of water stored in the lake basins. In the case of confluent lakes, we assumed highest stability of the volume of storage, whereas the lowest in contrafluent lakes.

(Fig. 1b); (c) contrafluent–confluent – which are supplied downstream during periods of lower water levels; the connection between the upstream limb of the lake and the river is activated only during higher water stages (Fig. 1c), and (d) profundal ones – this type encompasses deep lakes which are intensely supplied by groundwater (Fig. 1d) (Dawidek and Turczyński, 2006).

The study of floodplain lakes is complicated by their high seasonal hydrological dynamic in terms of water level fluctuations. These changes are very difficult to predict and do not occur in such extent in other kinds of lakes. This is the reason why the calculation and the comparison of water balance elements of floodplain lake basins rarely appears in the literature. The two functional phases are most important when assessing water balance for lake basins: potamophase, which refers to the connection of a lake with a river, and limnophase, which refers to a period in which the lake is isolated. The diversity of FPLs, which is a consequence of the type of lake's connection to the parent river, necessitates adopting a standard approach to calculating water balance for lake basins. A water balance equation for floodplain lakes and river valleys which appears in the literature
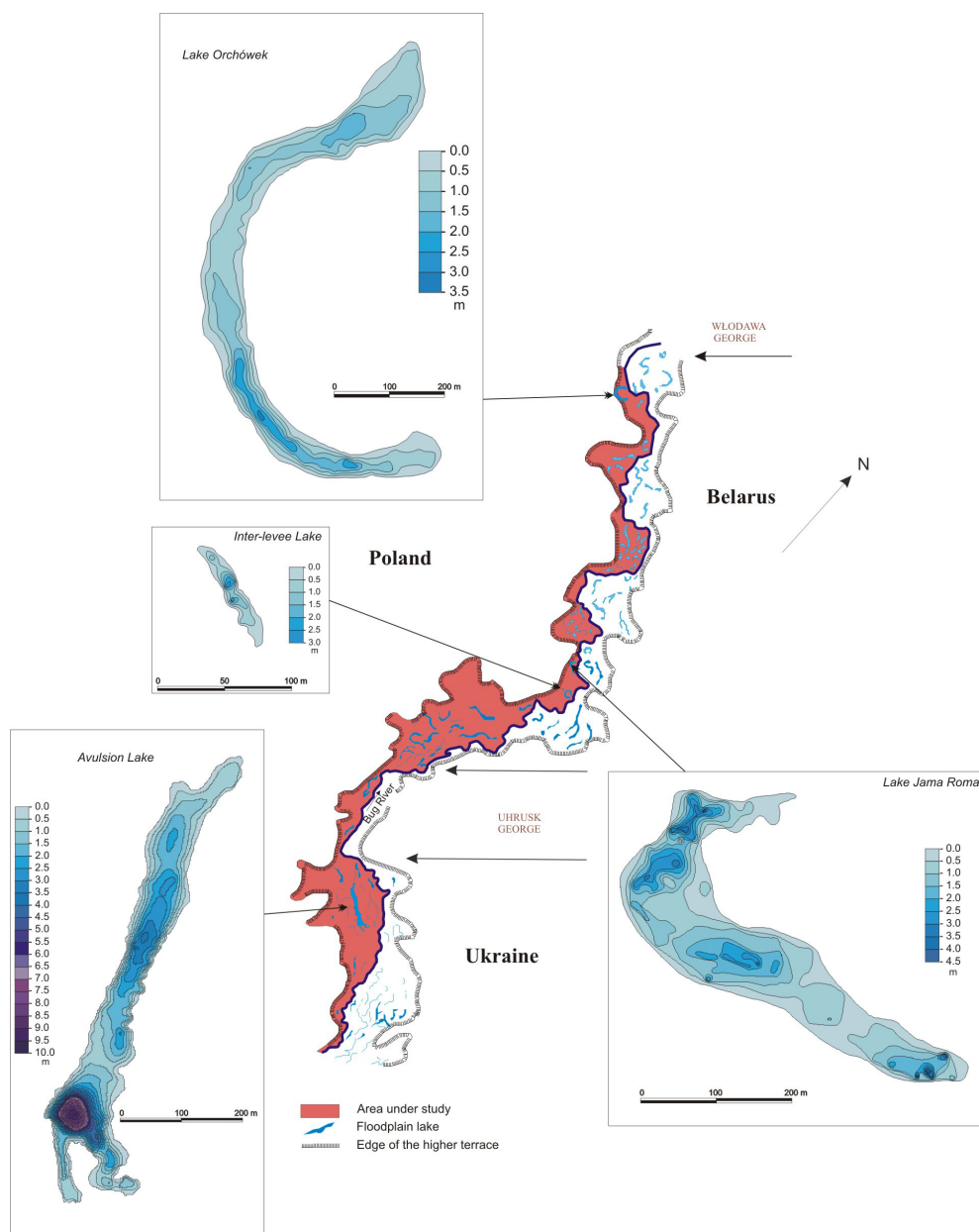
**Fig. 2.** Location and morphometry of the lakes under study.

Study area

Field observations were conducted in four floodplain lakes located in the valley of the Bug River between Wola Uhruska (to the south) and Włodawa (to the north). The functioning of all types of lakes, both genetic and hydrological ones, was studied in this area. The measurements of water balance components were carried out in typologically different lakes (Table 1). The climatic conditions of the Bug River basin are influenced by two substantial air masses: the polar maritime and the polar continental. Precipitation occurred most frequently in summer in the study period. Annual

sums of precipitation varied from $612\,\mathrm{mm\,yr^{-1}}$ in 2008 to $711\,\mathrm{mm\,yr^{-1}}$ in 2011. Annual mean temperature of the study period amounted to $8.8\,°\mathrm{C}$. The coldest month was February (mean temperature $-1.6\,°\mathrm{C}$), whereas the higher temperature occurred in July (monthly mean temperature amounted to $19.4\,°\mathrm{C}$).

The studied section of the Bug River is at the Polish border (at the same time the European Union's eastern border), which is why it has maintained its almost natural character. The section of the left (Polish) fraction of the Bug River has an area of $30\,\mathrm{km^2}$ and is situated between noticeable narrowings of the valley, which have a gorge-like character. The

Table 1. Selected characteristics of the lakes under study.

	Area (ha)	Volume (m^3)	Depth (m)	Hydrological type	Origin of the lake
Lake Orchówek	8.3	62 200	2.6	Contrafluent	Oxbow
Lake Jama Roma	5.0	47 100	4.9	Contrafluent–confluent	Oxbow
Inter-levee lake	0.1	700	2.5	Confluent	Inter-levee
Avulsion lake	5.5	89 000	10.3	Confluent–profundal	Avulsion
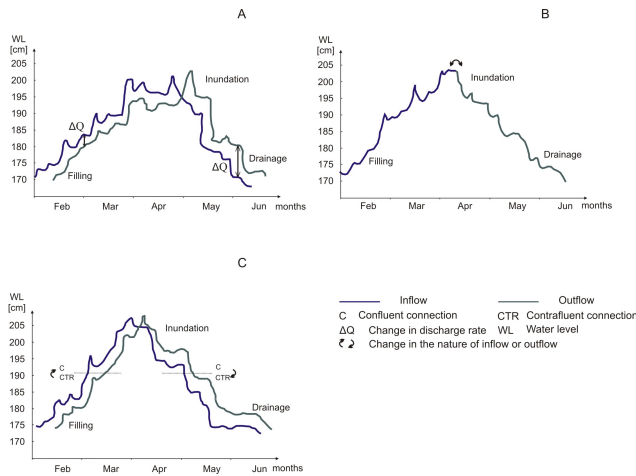
Fig. 3. Hydrographs of floodplain lakes under study depending on the connection to the Bug River: **(A)** – confluent lakes, **(B)** – contrafluent lakes, and **(C)** – contrafluent–confluent lakes.

western border of the study area was marked by the morphological edge of an older terrace, which was a noticeable terrain feature (Fig. 2).

2 Methods

2.1 The water balance for floodplain lake basins

There is a significant limitation to the practical applicability of the commonly used water balance equations. Namely, just as for floodplain lakes, they can only be used with regard to the cases and periods in which there is confluent inflow to lake basins (Fig. 3a).

A wide disparity between the volume of water feeding the floodplain lake basins (in a short time period) and the volume of the basins themselves makes balancing of water resources difficult. Generally, it can be said that the small storage capacity of lake basins is used up very quickly and that the lake supply dynamic necessitates intensive horizontal water exchange. The period of potamophase culmination is particularly important. At the time of the maximum rate of fluvial supply to the lakes, the values of lake water inflow and outflow are even (or very similar). A small storage capacity does not modify the transit of water through a basin in the slightest.

In case of contrafluent lakes, two equations should be solved separately: one for filling (Eq. 2), PF($+$), and the other for draining (Eq. 3), PF($-$), parts of potamophase.

$$(P - E) + I_{\text{CTR}} \pm \mathrm{d}S/\mathrm{d}t = 0, \qquad (2)$$

and

$$(P - E) - O_{\text{CTR}} \pm \mathrm{d}S/\mathrm{d}t = 0, \qquad (3)$$

where P denotes precipitation on the lake surface (m^3), E evaporation from the lake surface (m^3), I_{CTR} contrafluent inflow (m^3), O_{CTR} contrafluent outflow (m^3), and $\mathrm{d}S/\mathrm{d}t$ changes in storage (m^3).

This is necessary because of the difference between the components of fluvial water inflow and outflow during river supply or drainage to a basin. When, during potamophase, water stages rise, there is only water inflow to a basin and there is no active outflow (Fig. 3b). However, when water stages decrease there is only outflow and no inflow. The compatibility of the distribution of potamophase with monthly distribution occurs very rarely, which in practice makes it necessary to include both cases (often repeatedly) as part of 1 month for which the water balance is calculated.

Water balance equations for contrafluent–confluent lake basins have the most complicated form (Eqs. 4–5). This is because they combine both of the aforementioned cases to a varying extent. During the many months for which water balance is calculated, one should take into account fluvial contrafluent supply, with both the filling (PF$+$) and drainage (PF$-$) phase, and then confluent supply and drainage after the type of inflow to a basin has changed (Fig. 3c). After the threshold between contrafluent and confluent supply has been crossed, this complex cycle ends with the contrafluent drainage of a basin.

The equation for filling stage takes the following form:

$$(P - E) + I_{\text{CTR}} + (I_{\text{C}} - O_{\text{C}}) \pm \mathrm{d}S/\mathrm{d}t = 0, \qquad (4)$$

and for drainage stage:

$$(P - E) + (I_{\text{C}} - O_{\text{C}}) - O_{\text{CTR}} \pm \mathrm{d}S/\mathrm{d}t = 0, \qquad (5)$$

where P denotes precipitation on the lake surface (m^3), E evaporation from the lake surface (m^3), I_{C} confluent inflow (m^3), I_{CTR} contrafluent inflow (m^3), O_{C} confluent outflow (m^3), O_{CTR} contrafluent outflow (m^3), and $\mathrm{d}S/\mathrm{d}t$ changes in storage (m^3).

The duration of particular phases depends on both the rate of increase and decrease of river water stages and the altitude of the connecting crevasse. Therefore, in order to solve a water balance equation for contrafluent–confluent lakes, one must be particularly careful and consistent when making measurements of flow rates and maintain a necessary methodical coherence (the same measurement equipment) based on modern (precise) flow sensors.

2.2 Field measurements

The field measurements were carried out during water years 2007–2011. The amount of atmospheric deposition to the studied lakes was calculated based on daily measurement data obtained from the meteorological stations of the Institute of Meteorology and Water Management in Włodawa, Hańsk and Dorohusk. The atmospheric precipitation to particular floodplain lakes was calculated using Thiessen polygon method (Faisal and Gaffar, 2012). The amount of precipitation registered at the Włodawa station was adopted for Lake Orchówek; the amount recorded at the Hańsk station was applied to lakes located at the Zbereże section of the valley – Jama Roma and inter-levee lake – and the amount recorded at the Dorohusk station was adopted for the avulsion lake, which is located near the village of Wola Uhruska. Evaporation from the surface of the lake was calculated using Ivanov's formula, which was acceptable in similar studies (Leśny and Juszczak, 2005; Marciniak and Szczucińska, 2007; Ahmadi, 2012). An algorithm, which was based on the close relationship between the amount of evaporation from the surface of the lake and meteorological conditions, took into account the average monthly values of the air temperature and relative humidity. These parameters were measured at the Włodawa gauging station. The volume of the water storage was obtained by calculating the difference between the degree of lake basin repletion, which corresponded to the beginning and end of each month for which water balance was assessed (Eq. 6).

$$\mathrm{d}S/\mathrm{d}t = \mathrm{Ve} - \mathrm{Vb}, \tag{6}$$

where $\mathrm{d}S/\mathrm{d}t$ denotes changes in storage (m^3), Ve lake volume on the last day of a month (m^3), and Vb lake volume on the first day of a month (m^3).

A Nautilus 2000 flowmeter was used to establish the direction of water flow. Moreover, regular readings of lake water stages from staff gauges were made every day at 7:00 a.m. Discharge calculation using rating curve method brings about uncertainties resulting from for example unsteady flow conditions or seasonal variations of the state of vegetation (Di Baldassare and Montanari, 2009). Staff gauges with 1 cm scale were used in order to observe water levels. According to Smidth (2002) and Pappenberger et al. (2006), the errors of water level measurements are very small (1–2 cm). Flow rate measurements were taken once a week using Valeport 801 and Nautilus 2000 electromagnetic flowmeters. The current

flowmeters have a measuring range of 2.5 m s^{-1} and zero with an error of ± 2 mm s^{-1}. The degree of error amounts to 1 % of the range. Flow sensors were calibrated according to the recommended specifications of the manufacturers. Daily discharges of lake inflows and outflows were determined from a rating curve. A velocity–area method was used to calculate streams discharge, which was based on Eq. (7):

$$Q = Av, \tag{7}$$

where Q denotes stream discharge (L s^{-1}), A area of the cross section (dm^2), and v flow velocity (dm s^{-1}).

In order to reduce discharge calculation errors, we increased numbers of vertical segments of measurement along the cross section, according to the European ISO EN Rule 748 (1997). If the cross-section width ranged from 1 to 3 m, we took measurements every 1 dm; if the width ranged from 3 to 5 m, subsections were placed every 2 dm; and if cross section width exceeded 5 m, every 2.5 dm. Separate inflow and outflow rating curves were prepared for each stream from measurements of flow rate and channel cross section at the staff gauge locations. The volume of surface water that flowed into or out of the reservoir each day was calculated using the appropriate rating curves and level observations. R^2 exceeded 0.8 in case of every curve, $p < 0.05$. The curves lay within the range of water level values at which discharge was measured. Occasionally, weir measurement methods were used in inundated places (e.g. above a beaver dam). The cross-section area of overflow (A) and the flow velocity (v) were assessed using the aforementioned devices. Under the conditions of different discharge, approximately 50 to 80 measurements of water flow were made annually in cross sections (of both inlet and outlet) of each floodplain lake under study. This amounted to over 2500 measurements of flow rates taken during the study period. FRIEND procedure (Flow Regimes from International Experimental and Network Data) was used for a hydrograph division (to surface and groundwater inflow and outflow). The algorithm was prepared by the Institute of Hydrology in Wallingford (United Kingdom) as part of international cooperation IHP UNESCO. The calculating procedure was based on the construction of pentads periods, in which the minimum values of flow had to fulfil the $\mathrm{Qmin}_{i-1} > 0.9\,\mathrm{Qmin}_i > \mathrm{Qmin}_{i+1}$ condition. The points selected this way created a line which reflected the underground flow (base flow).

3 Results

3.1 Precipitation and evaporation

The highest (among the lakes under study) volumes of vertical water balance components occurred in Lake Orchówek. The volume of precipitation fluctuated between 50 788 and 58 988 m^3 yr^{-1}, with an average value of 54 310 m^3 yr^{-1} during the 5-year study period (Table 2). The amount of

Table 2. Water balance elements of the lakes under study ($m^3\,yr^{-1}$).

	P	E	I_{CTR}	I_C	Ig	O	Og	ΔS
				Lake Orchówek				
2007	52 473	49 375	614 881	n.o.	92 232	614 071	85 970	3908
2008	50 788	56 930	101 297	n.o.	11 143	101 050	10 003	−5896
2009	58 083	45 758	201 824	n.o.	18 164	192 876	36 646	21 273
2010	51 219	43 623	575 022	n.o.	155 256	563 683	62 005	18 935
2011	58 988	46 624	179 101	n.o.	25 074	169 096	42 274	22 369
				Lake Jama Roma				
2007	30 457	29 982	173 887	97 393	85 910	253 236	63 309	18 519
2008	30 270	34 570	9352	0	2712	4928	986	125
2009	38 032	27 786	50 020	54 277	11 355	103 589	2072	10 953
2010	33 496	26 489	132 381	38 153	28 453	167 362	15 063	10 179
2011	36 333	28 311	88 310	31 811	39 602	116 235	30 221	11 908
				Inter-levee Lake				
2007	695	684	n.o.	11 058	100	10 581	973	487
2008	691	789	n.o.	0	0	0	0	−98
2009	868	634	n.o.	34 915	300	34 655	693	494
2010	764	604	n.o.	26 237	1810	26 897	215	−500
2011	829	646	n.o.	10 638	3936	10 476	733	345
				Avulsion Lake				
2007	36 370	32 540	n.o.	2 217 410	1 444 912	2 640 984	1 822 279	5160
2008	37 732	37 519	n.o.	1 896 893	941 865	2 412 691	627 300	8964
2009	42 420	30 156	n.o.	606 134	402 984	846 004	363 782	−6463
2010	39 422	28 749	n.o.	4 407 331	3 547 039	4 810 480	2 645 764	25 358
2011	34 609	30 727	n.o.	3 571 940	3 104 085	3 968 647	3 214 604	−3414

P – precipitation on the lake surface, E – evaporation from the lake surface, I_{CTR} – contrafluent inflow, I_C – confluent inflow, O – outflow, Ig – groundwater inflow, Og – groundwater outflow, ΔS – changes in storage, n.o. – not occurred.

evaporation fluctuated slightly more, that is, between 45 758 and 56 930 $m^3\,yr^{-1}$ (the average value was 48 462 $m^3\,yr^{-1}$). Evaporation accounted from 79 % of the amount of precipitation in 2011 to 112 % in the driest year of 2008. The hydro-meteorological conditions in the first year of observations (2007) were the closest to the average conditions in the 5-year period. The amount of atmospheric precipitation to the lake Jama Roma clearly fluctuated in the period under study from 30 270 to 38 032 $m^3\,yr^{-1}$. The range of variability in the volume of water that evaporated from the surface of the lake was similar. Therefore, the meteorological conditions in the Zbereże section of the valley of the Bug River were fluctuating during the period under study, and their above-average dynamics represented a wet period. The lowest volumes of precipitation and evaporation were observed in the inter-levee lake. Precipitation in the lake surface area amounted from 691 to 868 $m^3\,yr^{-1}$. The range of evaporation volume was lower (Table 2). As a result, meteorological conditions of the lake might be considered as stable. The proportion of the amount of precipitation and evaporation in an avulsion lake in Wola Uhruska amounted from 71 % in 2009

to 99 % in 2008. The relatively stable conditions in which the vertical components of the hydrological balance of the lake were observed emphasised the extreme variability of fluvial components and an average variability of storage values.

3.2 Inflow and outflow

A high amplitude of water inflow and outflow was a derivative of the unstable conditions of Lake Orchówek supply. Volumes of horizontal elements of water balance were diverse (Table 2). Fluvial inflow in 4 out of 5 water years under study was higher than outflow. The relationships between filling and drainage stages of potamophases were also characteristic in this lake. A duration of the filling phase was longer (1–3 months) than the duration of drainage phase (2–3 weeks). As compared to the amounts of precipitation and evaporation, the values of horizontal components of the water balance for the lake Jama Roma were one order of magnitude higher (Table 2). In the 4 years of the study period, the volume of water inflowing into the lake basin was higher than the outflow. In 2007 water year potamophases lasted from February to April. Relations between its positive

(filling) and negative (drainage) parts were aligned. The relations were different during a long potamophase in the water year 2010. A filling of the lake continued, with a short interruptions, from November to March, while negative potamophase from April to July. The inflow volume was approximately three times higher than outflow during the positive potamophase (116 000 m^3 and 42 000 m^3, respectively). Drainage stage was shorter; however, a disparity between the outflow and inflow was lower at that time (134 000 m^3 and 97 000 m^3 respectively). In the inter-levee lake situated in Zbereże village, a clear similarity was observed between the volume of inflowing and outflowing water. During the water year of 2008, there was no lake connection to the Bug River. The percentage share of horizontal components in the water balance was definitely higher than the share of vertical ones (Table 2). Potamophases were transient in that lake, the longest in 2011 lasted 2 months (from December to February). A supremacy (both temporal and quantitative) of either filling or drainage was not observed during the time period under study. Different genetic forms of basin supply of avulsion lake in Wola Uhruska (fluvial and groundwater inflow) were various, whereas the dominance of the inflow from the river was constant. Underground inflow of this confluent–profundal lake varied from 0.7 to 2.7 % of total inflow. Lake outflow was active for most of the year. The lake stood out against the other lakes with regards to temporal and quantitative balance between positive and negative potamophases. Short potamophases (3–14 days) generally occurred in the first 2 years of observation. The time of lake connection to the river during the remaining period ranged from 2 months in 2011 to 10 months in 2010.

3.3 Storage conditions

Retention volume of Lake Orchówek ranged from −5896 to 22 369 m^3 yr^{-1}. In 2008, when the total annual atmospheric precipitation was the lowest, retention was negative and the volume of losses amounted to −5896 m^3 yr^{-1} (Table 2). The storage level was relatively even in the following years, and it ranged from 18 935 to 22 369 m^3 yr^{-1}. Jama Roma lake gained water throughout the study period. Changes in storage volume were pronounced and amounted from 125 m^3 yr^{-1} in water year 2008 to 18 519 m^3 yr^{-1} in 2007. High variability of retention volume was observed in the inter-levee lake (from −500 to 494 m^3 yr^{-1}). A significant change in the amount of water resources in the lake basin from year to year was recorded, which rarely occurs in lakes of a different origin. The volume of storage changes in the avulsion lake varied between −3414 and 25 358 m^3 yr^{-1}. During 2 years of the observation period, a shortage of water resources of the lake basin was observed. Storage volume fluctuations usually occurred repeatedly, that is, increased in the year following a decrease in the amount of water (Table 2).

4 Discussion and conclusions

The issue of assessing water balance for floodplain lakes has not received recognition from many researchers in global literature. The existing publications on FPLs usually deal with natural valleys of large rivers in South America and North America (Lesack and Melack, 1995; Schemel et al., 2004; Williams et al., 2004; Acreman et al., 2007; Phlips et al., 2008; Wren et al., 2008; Alcântara et al., 2010; Affonso et al., 2011). The channels of the majority of European rivers were at some stage modified; this made floodplain lakes disappear. The relatively few remaining water bodies are usually characterised by man-controlled water flow. The difficulties in comparing the water balance values obtained for floodplain lakes in the temperate zone of Europe to those of American floodplain lakes result from the pronounced differences in the flow rates. Hamilton and Lewis (1987) calculated the volume of fluvial water for the floodplain lakes of the Orinoco Valley in the phase of filling at approx. 8×10^6 m^3. The volume of the largest of the lakes under study was less than 9×10^4 m^3.

The hypothesis that a dominant role among water balance elements played fluvial inflow and drainage has been confirmed in the floodplain lakes for most of the study period. The hypothesis that fluvial inflow and drainage played a dominant role among water balance elements has been confirmed in the floodplain lakes for most of the study period. Disproportions between horizontal and vertical components were various, depending on the type of lake connection to the river. The highest differences were noted in flow-through confluent lakes. The volume of horizontally exchanged water in the confluent–profundal lake in Wola Uhruska was approximately 50 times larger than the average volume of precipitation and evaporation. The disparity between the components of the water balance equation for the confluent inter-levee lake in Zbereże was smaller. The horizontal water exchange rate resulting from confluent inflow was approximately 20 times higher than the vertical one in this lake. Lake Orchówek showed the smallest disparity between horizontal and vertical water balance components. This was connected with both natural factors and human pressure. The lake basin, which was supplied and drained via the same channel, was filled by the backwater of a river in a period of high water stages. A controlled (artificial) water distribution (a weir at the outflow), which was observed in the period under study, was designed to maintain water stages by decreasing outflow. The most stable relation between the elements of water balance occurred in the contrafluent–confluent lake Jama Roma. A supremacy of precipitation and evaporation volumes over river inflow and outflow was observed in 2008 water year, due to a lack of confluent inlet.

The structure of water balance equations for floodplain lakes in the area under study showed similarity. Horizontal component values considerably prevailed over vertical ones in majority of lakes. They were one order of magnitude (occasionally more) higher. Therefore, water balance

equations exposed the most important features which had determined the hydrological condition of floodplain lakes, and in a broader sense, also their hydro-biological and ecological state. Water storage in the lake basin was determined by volumes of precipitation and evaporation during periods with lack of confluent inflow (in 2008 in Jama Roma and inter-levee lakes). The level of water storage in the floodplain lakes under study varied significantly. The lowest capacity characterised inter-levee lake, which was distant from the Bug River. The complicated distribution of water supplying that confluent lake caused, after fluvial inflow had been stopped, the lake to still drain the floodplain water resources of its direct catchment while maintaining basin volume for some time. Water storage resulted from fluvial inflow, as well as during periods lacking confluent supply from a quantity of precipitation and evaporation (2008). The usually longer duration of the phase of filling in relation to the phase of drainage caused the volumes of inflow to be higher than the volumes of outflow in each year of observation, and it also determined an increased basin capacity. Storage value in lake Orchówek resulted from both the river supply and the quantity of evaporated water. Human pressure caused higher volume of inflow than the volume of outflow. Positive retention was observed in 4 out of the 5 years under study. In 2008, despite larger fluvial supply, water shortage occurred in the lake basin. Evaporation was facilitated by the damming up of water and the shallow lake basin. A high variability of fluvial inflow and drainage occurred in the avulsion lake. Volume of water stored in the lake basin was low in comparison with the lake volume as well as every measured form of lake feeding and drainage. Groundwater inflow played an important role. The highest value of storage occurred in periods with intensive groundwater inflow, whereas the lowest storage in years in which groundwater inflow was the lowest.

The 5-year period under study showed that the highest storage level accompanied the highest dynamics of discharge in lakes with undisturbed water distribution. The volume of the retained water was mostly determined by the orographic features of direct catchment area and, to a lesser extent, by morphometric factors of the lake basin. The hypothesis that retention volume results from the difference between fluvial inflow and outflow, with minimum role of atmospheric deposition, has not been confirmed. Jama Roma was the only water body which gained water in all the years in which fluvial inflow dominated over the outflow. However, quantity of gains and losses (in 2008–2011 period) was also determined by a relationship between precipitation and evaporation. In other lakes in water year 2008 and in the avulsion lake in 2007 and 2010 also, the volume of storage was not determined strictly by the river inflow and drainage. To conclude, the fluctuations in the volume of retention was not affected by the type of hydrological connection of the floodplain lake to the Bug River.

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