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

J. Dawidek[1] **and B. Ferencz**[2]

[1]Department of Hydrology, Maria Curie-Skłodowska University, Aleja Krasnicka 2 cd, 20-718 Lublin, Poland
[2]Department of Landscape Ecology and Nature Conservation, University of Life Sciences, Akademicka 13, 22-950 Lublin, Poland

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Correspondence to: B. Ferencz (beata.ferencz@up.lublin.pl)

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Abstract

This study is the first attempt in the literature on the subject of comparing water balance equations for floodplain lake basins depending on the type of connection the lake has to its parent river. Where confluent lakes (upstream connections) were concerned, it was only possible to apply a classic water balance equation. When dealing with contrafluent lakes (downstream connections) as well as lakes with a complex recharge type (contrafluent–confluent) modified equations were created. The hydrological type of a lake is decided by high water flow conditions and, consequently, the duration of potamophase (connection with a river) and limnophase (the isolation of the lake), which determine the values of particular components and the proportion of the vertical to horizontal water exchange rate.

Confluent lakes are characterised by the highest proportion of horizontal components (the inflow and runoff of river water) to the vertical ones (precipitation and evaporation). The smallest differences occur with respect to a contrafluent lake. In the case of confluent lakes, the relationship between water balance components resulted from the consequent water flow through the basin, consistent with the slope of the river channel and valley. The supplying channels of contrafluent lakes had an obsequent character, which is why the flow rate was lower. Lakes with a complex, contrafluent–confluent recharge type showed intermediate features. After a period of slow contrafluent recharge, the inflow of water through a downstream crevasse from the area of the headwater of the river was activated; this caused a radical change of flow conditions into confluent ones. The conditions of water retention in lake basins were also varied. Apart from hydrological recharge, also the orographic features of the catchment areas of the lakes played an important role here, for example, the distance from the river channel, the altitude at which a given catchment was located within the floodplain and the complexity of the channels of fluvial-water inflow.

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1 Introduction

Floodplain lakes (FPL) 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 FPL: 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, however, 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).

Four functional phases can be distinguished on the basis of the seasonal fluctuations of the hydrochemical parameters of a basin: filling, flow-through, drainage and isolation (Hamilton and Lewis, 1987; Garcia de Emiliani, 1997). This 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 Danube River: (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 recharged 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. 1c); (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. 1b), and (d) profundal ones – this type encompasses deep lakes which are intensely supplied by groundwater (Fig. 1d) (Dawidek and Turczyński, 2006).

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The study of floodplain lakes is complicated by their high hydrological and seasonal dynamics which are very difficult to predict and which do not occur in other kinds of lakes. This is why the calculation of water resources and the comparison of water balance equations for floodplain lake basins very 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 hydrological diversity of FPLs, which is a consequence of the recharge type, 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 (Lesack, 1993; Bonnet et al., 2008; Sriwongsitanon et al., 2009; Alsdorf et al., 2010) can be presented as follows:

$$(P - E) + (I - O) \pm \Delta S = 0 \quad (1)$$

where: P – precipitation, E – evaporation from lake surface, I – inflow to the lake basin, O – outflow, ΔS – 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 recharge to floodplain lake basins which, due to their depth, act as a local drainage base for the water-bearing zone. The role of profundal recharge rises in the period of limnophase, as it is the only form of recharge in basins during periods without rainfall. The possibility of the occurrence of both potamophase and limnophase in the same month is an important matter when one assesses lake water balance while maintaining the structure of monthly equations. Then the values of equation components which are derivatives of vertical water exchange (precipitation–evaporation) become modified. Due to the natural character of the valley of the Bug River, the modifications of water flow result from

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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 a lake. Another factor that hinders hydrometric measurements is the damming up of water due to the overgrowing of crevasses in summer and the formation of ice cover in winter. 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 of the water storage of a lake.

This paper aims to calculate and analyze the water balance elements of floodplain lake basins, depending on the lake recharge type (type and degree of the connection between the lake and the parent river). The significantly 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 $m^3 s^{-1}$ allows for the assumption that horizontal water balance elements (fluvial) dominate in the water balance of the lakes. We hypothesized that the type of connection between a floodplain lake and its parent river determines the relationship between vertical and horizontal water balance elements.

2 Study area

Field observations were conducted in 4 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. Detailed observations of water balance components were carried out in typologically different lakes (Table 1).

This section of the Bug River is on, and forms part of, the eastern Polish border (simultaneously acting as the eastern border of the EU) which is why it has maintained its almost natural character. The studied section of the left (Polish) fraction of the Bug River has an area of 30 km^2 and is situated between noticeable narrowings of the valley which have a gorge-like character. The western border of the study area was marked by the morphological edge of an older terrace which was a noticeable terrain feature (Fig. 2).

3 Methods

3.1 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 recharge to lake basins (Fig. 3a).

Although the structure of the equation is simple, it is not easy to obtain reliable results. This is related to the wide disparity between the volume of water feeding the floodplain lake basins (in a short time period) and the volume of the basins themselves. Generally, it can be said that the small storage capacity of lake basins is used up very quickly and that the lakes supply dynamic necessitates intensive horizontal water exchange. Consequently, periodical (even daily) observations are not sufficient to carry out water balance calculations because it happens that the time of flow of the water through a lake basin is shorter than 24 h and the recorded rates of inflow and outflow (e.g. once a day) represent an overly long time interval. 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.

Slightly different problems arise during attempts at comparing water balance equations for contrafluent lakes. In this case two equations should be solved separately; one for filling (Eq. 2) PF(+) and the other for draining (Eq. 3) PF(−) parts of potamophase.

$$(P - E) + I \pm \Delta S = 0 \quad (2)$$

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and

$$(P - E) - O \pm \Delta S = 0 \quad (3)$$

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 one 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 recharge, with both the filling (PF+) and drainage (PF−) phase, and then confluent supply and drainage after the type of recharge to a basin has changed (Fig. 3c). After the threshold between contrafluent and confluent recharge has been crossed, this complex cycle ends with the contrafluent drainage of a basin.

The equation for positive potamophase (filling stage) takes the following form:

$$(P - E) + I + (I - O) \pm \Delta S = 0 \quad (4)$$

and for negative potamophase (drainage stage):

$$(P - E) + (I - O) - O \pm \Delta S = 0. \quad (5)$$

The duration of particular phases depends on the rate of increase and decrease of river water stages and the altitude at which the point where the direction of the vector of the movement of recharge to a floodplain lake basin changes. Therefore, in order to solve a water balance equation for contrafluent–confluent lakes, one must be particularly

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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.

3.2 Field measurements

The territorial research was 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 supply to particular floodplain lakes was calculated by using the polygon method. 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 an important factor in the water balance equations. The most precise method of obtaining its value is by use of evaporimeter measurements. The lack of possibility of making such measurements in the area under study combined with the available range of meteorological data determined the use of Ivanov's formula, which is 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 water and meteorological conditions, took into account the average monthly values of the air temperature and relative humidity. These parameters were only measured at the Włodawa gauging station, this excluded the possibility of examining the spatial variability of this phenomenon. The volume of the water storage of the lakes was obtained by calculating the difference between the degree of basin repletion, which corresponded to the beginning and end of each month for which water balance was assessed, as converted into water volume (Eq. 6).

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$$\Delta S = \mathrm{Ve} - \mathrm{Vb} \quad (6)$$

where: S – storage, Ve – lake volume on the last day of a month, Vb – lake volume on the first day of a month .

Monthly values of lake water balance components were used to calculate annual water balance equations. A Nautilus 2000 flow meter was used to establish the direction of water flow. Moreover, regular readings of lake water stages from staff gauges were made every day at 07:00 UTC Discharge calculation using rating curve method bring about uncertainities resulted from e.g. 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 observed water levels (WL). 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 Velaport 801 and Nautilus 2000 electromagnetic flow meters. The current meters have a measuring range of 2.5 $\mathrm{m\,s^{-1}}$ and zero with an error of ±2 $\mathrm{mm\,s^{-1}}$. 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. It was based on the relationship presented in Eq. (7).

$$Q = A \cdot v \quad (7)$$

where Q – stream discharge [$\mathrm{dm^3\,s^{-1}}$], A – area of the cross section [$\mathrm{dm^3}$], v – flow velocity.

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 take 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

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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. The curves lied within the range of water level values at which discharge was measured. Weir measurement methods were used in places which were particularly hard to access: the cross-section area of overflow (A) and the flow velocity (v), using the aforementioned devices, were assessed (e.g. above a beaver dam). For each of the lakes where weir measurement methods were used the channels of water supply to lake basins were identified. Under the conditions of different discharge, approximately 50–80 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 underground inflow and outflow). The algorithm was prepared by the Institute of Hydrology, Wallingford (UK) 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).

4 Results

In Lake Orchówek the volume of precipitation clearly fluctuated between 50 788 and 58 988 $\mathrm{m}^3\,\mathrm{yr}^{-1}$, with an average value of 54 310 $\mathrm{m}^3\,\mathrm{yr}^{-1}$ during the five-year study period. The amount of evaporation fluctuated slightly more, that is, between 45 758 and 56 930 $\mathrm{m}^3\,\mathrm{yr}^{-1}$ (the average value was 48 462 $\mathrm{m}^3\,\mathrm{yr}^{-1}$). Evaporation accounted for 79 % of the amount of precipitation in 2011 to 112 % in the driest year of 2008. A high amplitude of water inflow and outflow was a derivate of the changeable recharge conditions.

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The dynamic changes in the amount of flowing water also resulted from the small storage capacity of the lakes. The order of magnitude of the difference between the absolute value of atmospheric precipitation and of river inflow and outflow was typical and persisted throughout the observation period. Underground lake basin's supply amounted from circa 100 000 $m^3 yr^{-1}$ in 2008 to over 600 000 $m^3 yr^{-1}$ in 2007. The outlet proportions were similar. Underground supply constituted from 3 % of the total inlet in 2010 to 62 % in 2008. Underground outlet share amounted from 10 % in 2008 to 25 % in 2011 (Table 2). The hydro-meteorological conditions in the first year of observations (2007) were the closest to the average conditions in the five-year period. Thus, the lake storage level, which corresponded to these conditions amounted to 3908 $m^3 yr^{-1}$, and it was regarded as typical of the study period. In 2008, when the total annual atmospheric precipitation was lowest, retention was negative and the volume of losses amounted to −5896 $m^3 yr^{-1}$. The storage level was relatively even in the following years and it ranged from 18 935 to 22 369 $m^3 yr^{-1}$. The components of water balance equations for Lake Orchówek showed considerable variability during each year of the study period (Table 2).

The amount of atmospheric precipitation to 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 changeable during the period under study and their above-average dynamics represented a wet period. As compared to the amounts of precipitation and evaporation, the values of horizontal components of the water balance for Lake Jama Roma were one order of magnitude higher (Table 2). The share of underground inflow in the total supply of the lake basin varied from 11 % in 2009 to 30 % in 2007 and 2011. The role of underground outlet was less stable and ranged from 2 % to over 20 % of total outlet. In each year water was stored in the lake basin.

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,

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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). Both underground inlet and outlet was the least stable among the lakes under study. The level of water storage was also very changeable. A radical change in the amount of water resources in the lake basin from year to year was recorded, this rarely occurs in lakes of a different origin. The proportion of the amount of precipitation and evaporation in an avulsion lake in Wola Uhruska changed insignificantly and it 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. Different genetic forms of basin supply (fluvial and groundwater recharge) were changeable, whereas the dominance of the recharge from the river was constant. High level of groundwater supply led to the equalisation of the water stages of the lake, especially during long limnophase periods without rainfall. The volume of storage changes in the avulsion lake varied between –3414 and 25 358 $m^3\,yr^{-1}$. During two 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).

5 Conclusion and discussion

The structure of water balance equations for floodplain lakes in the area under study showed a distinct similarity. In all cases, horizontal component values considerably prevailed over vertical (atmogenic) ones, that is, 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.

In each of the studied lakes, water stages were determined by the volume of the inflowing water and the water drained by the parent river for most of the observation period. Confluent lakes with a transit flow of flooding water through the basins were characterised by the largest disparity between vertical and horizontal water balance components. The share of underground inlet in total basin supply was the highest among the lakes under study, which was connected with lake depth (over 10 m) and its location within the valley narrowing section. 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 inter-levee lake in Zbereże was smaller, but still very large. The horizontal water exchange rate resulting from confluent recharge was approximately 20 times higher than the vertical one in these lakes. Extreme storage values with reference to the other lakes under study were observed in the lake basin. The five-year period under study showed that the highest storage level accompanied the highest dynamics of discharge, whereas the volume of the stored 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 inter-levee lake water, which was located relatively far from the parent river, was characterised by long and complex recharge channels and a relatively large direct catchment area. The complicated distribution of water supplying that confluent lake determined the small volume of the fluvial recharge, as well as similar values of surface inflow and outflow. After potamic recharge had been stopped, the lake still drained the floodplain water resources of its direct catchment while maintaining basin capacity for some time. Complex quantitative relations between underground inlet and outlet resulted from the basin origin. Inter-levee lake originated from the deposition processes, unlike any other lake under study. It resulted in higher altitude of the lake basin. Both basin supply and drainage showed relationship with water table elevation within the river valley. The relatively small volume of both precipitation and evaporation was a consequence of the very small area of the lake. The storage volume of the lake basin was determined by the input of river water and also, unlike in the other lakes under study, the values of vertical water balance components. Contrafluent–confluent recharge to Lake Jama Roma initially facilitated

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the "pumping" of the lake via a downstream crevasse. In periods when the water level was rising, flow velocity was relatively low (data not presented). During the decrease of the water level in the river channel, the lake was slowly drained. 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. Similarities of underground inlets and outlets were a result of maximum depth of the lake basin (4.9 m). Deep lake easily drained the water table. 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 (similar to Lake Jama Roma), 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. As a consequence, the volume of the inflowing water was higher than the volume of outflow. A disparity between underground inlet and outlet during the time period under study resulted from artificial water distribution. The storage level depended both on the exchange of water with a river and the quantity of evaporated water. In 2008, despite a larger fluvial supply, a water shortage occurred in the lake basin. Evaporation was facilitated by the damming up of water and the shallow lake basin.

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 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 Amer-

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ican floodplain lakes result from the pronounced differences in the flow rates. Hamilton and Lewis (1987) calculated the volume of potamic 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.

References

Acreman, M. C., Fisher, J., Stratford, C. J., Mould, D. J., and Mountford, J. O.: Hydrological science and wetland restoration: some case studies from Europe, Hydrol. Earth Syst. Sci., 11, 158–169, doi:10.5194/hess-11-158-2007, 2007.

Affonso, A. G., de Queiroz, H. L., and de Moraes Novo, E. M. L.: Limnological characterization of floodplain lakes in Mamirauá Sustainable Development Reserve, Central Amazon (Amazonas State, Brazil), Acta Limnol. Bras., 23, 95–108, doi:10.4322/actalb.2011.023, 2011.

Ahmadi, M. A.: Evaluation of tourism climate comfort in order to attract more tourists – case study: Sanandaj city in Iran, Life Sci. J., 9, 623–629, 2012.

Alcântara, E., Novo, E., Stech, J., Lorenzzetti, J., Barbosa, C., Assireu, A., and Souza, A.: A contribution to understanding the turbidity behaviour in an Amazon floodplain, Hydrol. Earth Syst. Sci., 14, 351–364, doi:10.5194/hess-14-351-2010, 2010.

Alsdorf, D., Han, S. C., Bates, P., and Melack, J.: Seasonal water storage on the Amazon floodplain measured from satellites, Remote Sens. Environ., 111, 2448–2456, doi:10.1016/j.rse.2010.05.020, 2010.

Amoros, C. and Bornette, G.: Connectivity and biocomplexity in water bodies or riverine floodplains, Freshwater Biol., 47, 761–776, 2002.

Bonnet, M. P., Barroux, G., Martinez, J. M., Seyler, F., Moreira-Turcq, P., Cochonneau, G., Melack, J. M., Boaventura, G., Maurice-Bourgoin, L., León, J. G., Roux, E., Calmant, S., Kosuth, P., Guyot, J. L., and Seyler, P.: Floodplain hydrology in an Amazon floodplain lake (Lago Grande de Curuaí), J. Hydrol., 349, 18–30, doi:10.1016/j.jhydrol.2007.10.055, 2008.

Chmiel, S., Dawidek, J., Szwajgier, W., and Turczyński, M.: Genetic types and transformations of lakes in the Middle Bug valley-floor, Limnol. Rev., 3, 31–36, 2003.

Dawidek, J. and Ferencz, B.: Hydrological processes in the riverine systems, the origin and classifications of floodplain lakes, Ecológia (Bratislava), 31, 331–340, doi:10.4149/ekol_2012_03_331, 2012.

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Dawidek, J. and Turczyński, M.: Feeding of lakes in the middle Bug River valley by river waters, Limnol. Rev., 7, 65–72, 2006.
Di Baldassarre, G. and Montanari, A.: Uncertainty in river discharge observations: a quantitative analysis, Hydrol. Earth Syst. Sci., 13, 913–921, doi:10.5194/hess-13-913-2009, 2009.
Drago, E. C.: Origen y clasificacion de ambientes leneticos en llanuras alluviales, Revista de la Asociacion de Ciencias Naturales Argentina, 7, 123–137, 1976.
Drago, E. C.: Morphological and hydrological characteristic of the floodplain ponds of the Middle Parana River (Argentina), Rev. Hydrobiol. Trop., 22, 183–190, 1989.
EU ISO EN 748:1997: Measurement of liquid flow in open channel – Velocity-area methods, 1997.
García de Emiliani, M. O.: Effects of water level fluctuations on phytoplankton in a river-floodplain lake system (Paraná River, Argentina), Hydrobiologia, 357, 1–15, 1997.
Hamilton, S. K. and Lewis, W. M.: Causes of seasonality in the chemistry of a lake on the Orinoco River floodplain, Venezuela, Limnol. Oceanogr., 32, 1277–1290, 1987.
Henry, R. and Costa, M. L. R.: As macrófitas como fator de heterogeneidade espacial: um estudo em três lagoas com diferentes conectividades com o rio Paranapanema, in: Ecologia e Manejo de Macrófitas Aquáticas, edited by: Thomaz, S. M. and Bini, L. M., EDUEM, Maringá, 189–210, 2003.
Hutchinson, G. E.: A Treatise of Limnology, Wiley, New York, 1015 pp., 1957.
Junk, W. J.: The Central Amazon Floodplain: Ecology of a Pulsing System, Ecological Studies 126, Springer, Berlin, 525 pp., 1997.
Junk, W. J., Bayley, P. B., and Sparks, R. E.: The flood pulse concept in river floodplain systems, Can. Spec. Publ. Fish. Aquat. Sci., 106, 110–127, 1989.
Lesack, L. F. W.: Water balance and hydrologic characteristics of a rainforest catchment in the central Amazon basin, Water Resour. Res., 29, 759–773, 1993.
Lesack, L. F. W. and Melack, J. M.: Flooding hydrology and mixture dynamics of lake water derived from multiple sources in an Amazon floodplain lake, Water Resour. Res., 31, 329–345, 1995.
Leśny, J. and Juszczak, R.: Evaluation of evapotranspiration of areas located within the zone of direct impact of small water reservoirs in agricultural landscape, Acta Agrophys., 6, 161–174, 2005.
Marciniak, M. and Szczucińska, A.: Measurements of selected water balance components in Ebbaelva catchments, Svalbard – pilot study, Landform Analys., 5, 51–54, 2007.

Pappenberger, F., Matgen, P., Beven, K. J., Henry, J. B., Pfister, L., and de Fraipont, P.: Influence of uncertain boundary conditions and model structure on flood inundation predictions, Adv. Water Resour., 29, 1430–1449, doi:10.1016/j.advwatres.2005.11.012, 2006.
Phlips, E. J., Havens, K. E., and Marques Lopes, M. R.: Seasonal dynamics of phytoplankton in two Amazon floodplain lakes of varying hydrologic connectivity to the main river channel, Arch. Hydrobiol., 172, 99–109, doi:10.1127/1863-9135/2008/0172-0099, 2008.
Schemel, L. E., Sommer, T. R., Müller-Solger, A. B., and Harrell, W. C.: Hydrologic variability, water chemistry, and phytoplankton biomass in a large floodplain of the Sacramento River, CA, USA, Hydrobiologia, 513, 129–139, 2004.
Smidth, A. R.: Analysis of stage–discharge relations for open-channel flows and their associated uncertainties, PhD thesis, University of Illinois, Urbana Champaign, 2002.
Sriwongsitanon, N., Surakit, K., and Hawkins, P. R.: A water balance budget for Bung Boraphet – a flood plain wetland-reservoir complex in Thailand, Water, 1, 54–79, doi:10.3390/w1010054, 2009.
Tockner, K., Pennetzdorfer, D., Reiner, R., Schiemer, F., and Ward, J. V.: Hydrological connectivity and the exchange of organic matter and nutrients in a dynamic river–floodplain system (Danube, Austria), Freshwater Biol., 41, 521–535, 1999.
Tockner, K., Malard, F., and Ward, J. V.: An extension of the flood pulse concept, Hydrol. Process., 14, 2861–2883, 2000.
Williams, M. R., Filoso, S., and Lefebvre, P.: Effects of land-use change on solute fluxes to floodplain lakes of the central Amazon, Biogeochemistry, 68, 259–275, 2004.
Wren, D. G., Davidson, G. R., Walker, W. G., and Galicki, S. J.: The evolution of an oxbow lake in the Mississippi alluvial floodplain, J. Soil Water Conserv., 63, 129–135, 2008.

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Table 1. Selected characteristics of the lakes under study.

	Area [ha]	Volume [m^3]	Depth [m]	Recharge type	Genetic type
Lake Orchówek	8.3	62 200	2.6	Contrafluent	Oxbow
Lake Jama Roma	5.0	47 100	4.9	Contrafluent–confluent	Oxbow
Inter-leeve lake	0.1	700	2.5	Confluent	Inter-levee
Avulsion lake	5.5	89 000	10.3	Confluent–profundal	Avulsion

Table 2. Water balance elements of the lakes under study [$m^3 yr^{-1}$].

	P	E	I_{CTR}	I_C	I_g	O	O_g	ΔS
Lake Orchówek								
2007	52 473	49 375	614 881	–	92 232	614 071	85 970	3908
2008	50 788	56 930	101 297	–	11 143	101 050	10 003	−5896
2009	58 083	45 758	201 824	–	18 164	192 876	36 646	21 273
2010	51 219	43 623	575 022	–	155 256	563 683	62 005	18 935
2011	58 988	46 624	179 101	–	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	–	11 058	100	10 581	973	487
2008	691	789	–	0	0	0	0	−98
2009	868	634	–	34 915	300	34 655	693	494
2010	764	604	–	26 237	1810	26 897	215	−500
2011	829	646	–	10 638	3936	10 476	733	345
Avulsion Lake								
2007	36 370	32 540	–	2 217 410	1 444 912	2 640 984	1 822 279	5160
2008	37 732	37 519	–	1 896 893	941 865	2 412 691	627 300	8964
2009	42 420	30 156	–	606 134	402 984	846 004	363 782	−6463
2010	39 422	28 749	–	4 407 331	3 547 039	4 810 480	2 645 764	25 358
2011	34 609	30 727	–	3 571 940	3 104 085	3 968 647	3 214 604	−3414

P – precipitation, E – evaporation, I_{CTR} – contrafluent inflow, I_C – confluent inflow, O – outflow, I_g – groundwater inflow, O_g – groundwater outflow, ΔS – changes in storage.

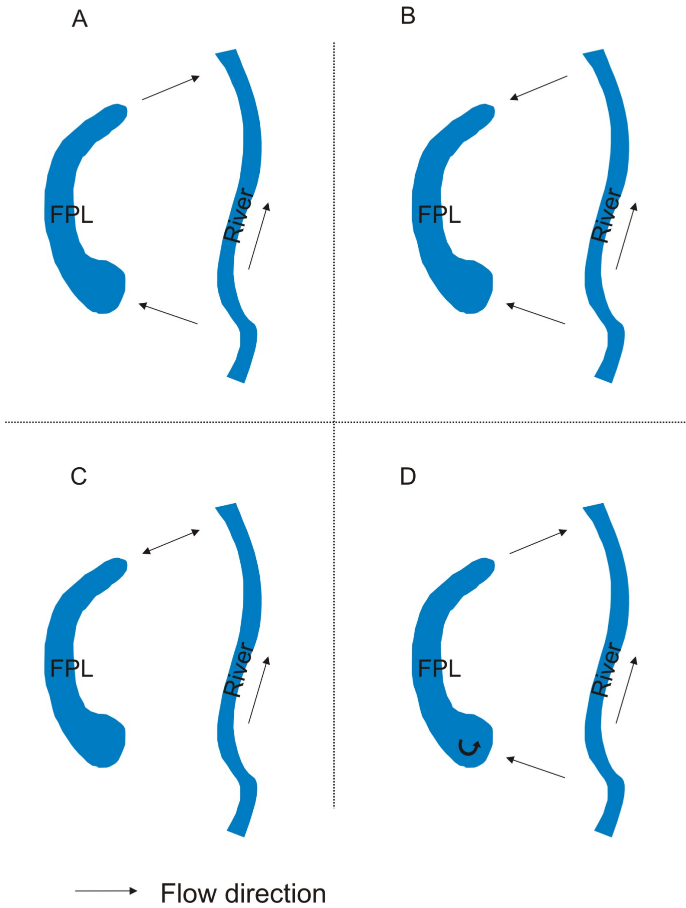

Fig. 1. Recharge types of floodplain lakes: **(A)** – confluent recharge, **(B)** – contrafluent-confluent recharge, **(C)** – contrafluent recharge, **(D)** – profundal recharge.

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Fig. 2. Location of the lakes under study.

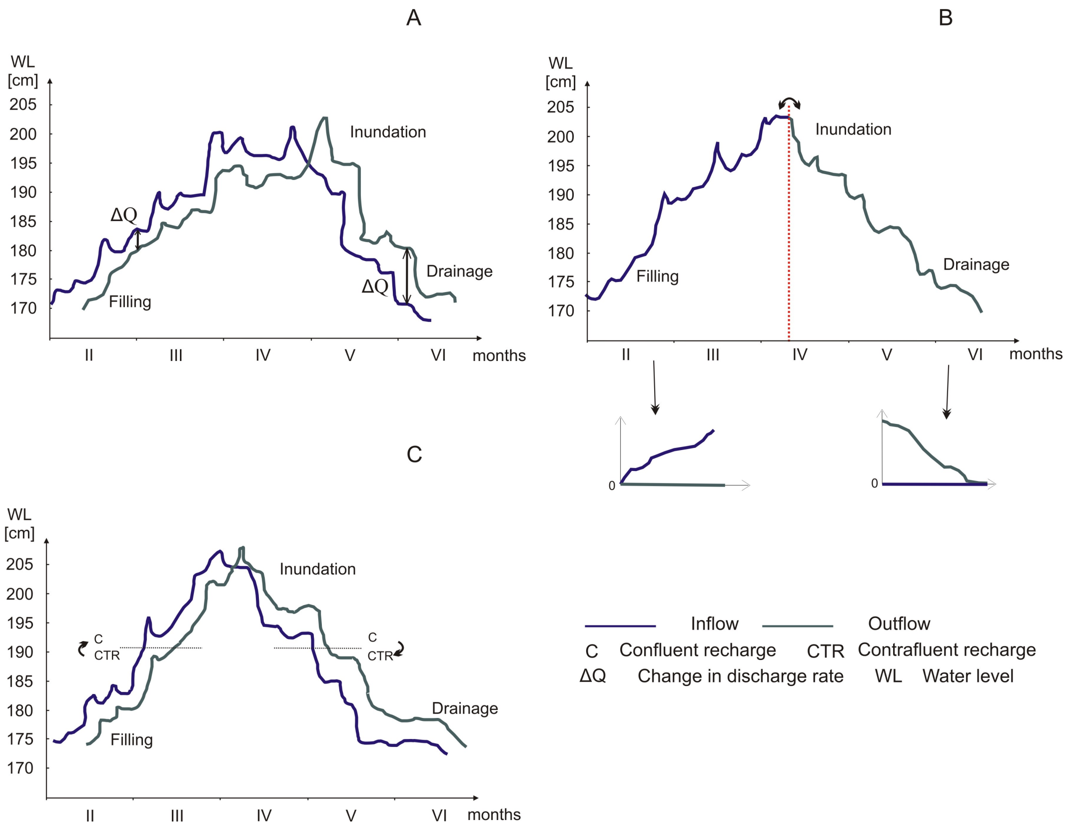

Fig. 3. Diagram of the floodplain lakes recharge type: **(A)** – confluent lakes, **(B)** – contrafluent lakes, **(C)** – contrafluent-confluent lakes.