Hydrol. Earth Syst. Sci. Discuss., 11, 13145–13174, 2014
www.hydrol-earth-syst-sci-discuss.net/11/13145/2014/
doi:10.5194/hessd-11-13145-2014

Hydrology and Earth System Sciences
Discussions
Open Access

Analysis of frequency and duration of the functional periods on the basis of long-term variability of limnetic processes within the Bug River valley

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Received: 20 September 2014 – Accepted: 11 November 2014 – Published: 1 December 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Floodplain lakes (FPLs) constitute a very important element of river valleys, both in terms of ecology and hydrology. Dynamic physicochemical, morphometric and biological changes of lake waters are determined by the variability of the functional periods of lakes: limnophases, potamophases and inundations. This paper presents factors that shape long-term dynamics of the frequencies and durations of potamophases and limnophases in 20 selected FPLs. The study area included the left fraction of the Bug River valley located at the European Union's eastern border stretched along countries like Poland, Ukraine, and Belarus. The analysis covered the water years 1952 to 2013. Assigning the value of Limnological Effective Rise (LER) was essential for determining the functional periods for each of the study lakes. The dynamics of the phenomenon was analysed using volatility indicators, while factors determining functional periods were distinguished using Principal Component Analysis (PCA). Results showed that short (0–8 days) and medium-length limnophases were observed most frequently during the study period. In the case of potamophases they most often lasted from 8 to 30 days, continuously. Double-mass curves showed four periods of increasing significance of one of the functional phases: 1952–1962 (limnophases), 1963–1982 (potamophases), 1983–1997 (limnophases) and 1998–2013 (potamophases). A variability that was observed in each floodplain lake under study resulted from two main factors: water input and lake basin morphometry. The major role in FPLs' input was played by potamic supply (inflow of water from the parent river), which was a derivative of Bug River water stages and discharge. Atmospheric precipitation played a smaller role. However, the role of local precipitation was marginal in relation to precipitation in the upper part of the Bug River catchment. Spatial variability of the frequencies and durations of potamophases and limnophases was also associated with the topography of the floodplain lake catchments. Hydrological connection to the river favoured (confluent lakes) or limited (contrafluent and contrafluent–confluent lakes) the frequencies of potamophases in the study period of 62 years.

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1 Introduction

River valleys and especially alluvial terraces are dynamic areas in terms of geographical, biological and chemical changes (Sparks et al., 1990) and heterogeneous ecosystems, which are associated with fluvial dynamic of the parent river (Hamilton et al., 1996; Drago et al., 2003; Marchese et al., 2008). Inundation periods cause morphological and ecological transformation of the floodplains (Hughes and Rood, 2001; Ward et al., 2002). Dynamic ecological changes of the inundation areas should be analysed in the temporal and spatial scales (Swales et al., 1999; Tockner et al., 2010). Biodiversity and habitat quality depend on many factors, with wetland connection to the river being the dominant one (Frazier and Page, 2006; Balcombe and Arthington, 2009). Although more than 90 % of floodplain areas in Europe and North America have been transformed (due to embankments, draining and conversion into agricultural lands) (Tockner and Stanford, 2002; Drago et al., 2008; Schomaker and Wolter, 2011), the Bug River, especially the fraction in the European Union's eastern border (section between Poland, Ukraine, and Belarus), has maintained a quasi-natural character.

Floodplain lakes are essential elements of the river valleys with low intensity of human activities. They increase retention capacity of the valley and serve as habitat for many species of water birds and other animals (Qi et al., 2009). The starting point for limnologic analysis of FPLs remains the flood-pulse concept of Junk (Junk et al., 1989). Although the importance of the flood-pulse concept has been widely recognized (Poff et al., 1997), quantification of the relationship between river discharge and floodplain inundation patterns, including water body connectivity, has received little attention in the context of ecological functioning of river–floodplain systems (Vaughan et al., 2009). There are three major periods in the functional cycle of floodplain lake: (a) potamophase, when hydraulic connectivity between lake and the parent river is observed, (b) limnophase, when the FPL is isolated from the river inflow, and (c) inundation, when entire floodplain is flooded, and floodplain lake basins lose their identity (Dawidek and Ferencz, 2012). The study of hydrodynamic processes occurring in the

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lake basins is an important and complex issue. Variability of periodical potamophases (PF) and limnophases (LF) in ecosystems of flooded river valleys is extremely important (Camargo and Esteves, 1996). Hydrological dynamics and lateral connectivity determine the ecological processes in FPLs (Poff and Allan, 1995; Duranel et al., 2007). Flood water that flows through the valley and the floodplain lake basin is characterized by repetitive intensity (periodic, seasonal or perennial) and circulation, resulting in a dynamic limnetic equilibrium, and in a broader sense also the ecosystem equilibrium. The final effect of biotic and abiotic processes of the aquatic environment of the valley is a specific condition of the FPL, both quantitative and qualitative.

The importance of the functional periods of the FPLs is determined by two groups of factors, both extra-zonal and inter-zonal in nature. In the first case, the lake conditions such as water level, the exchange rate and quality parameters, are shaped by the input from the catchment area of the parent river (Tockner et al., 2000). Most often, this is a very large surface area in relation to a floodplain. Moreover, the river catchment is often diverse in terms of geology, topography or even climate conditions. Inflow of flood water (potamic supply) rapidly and for a long time changes the floodplain lake, both quantitatively and qualitatively. Inter-zonal factors prevail during limnophase period, when the FPL is supplied with water from its own catchment area. The limnetic processes are slower and their intensity differs from that during the potamophase period. The high heterogeneity of floodplain lakes conditions is observed during the limnophase.

The aim of the study was to determine the variability of the functional periods of selected FPLs. Long-term analysis of the frequency and duration of potamophases (PF) and limnophases (LF) has been performed for 20 floodplain lakes located in the Middle Bug River valley, in conjunction with the dynamics of the parent river stages. Knowledge of the spatial and temporal patterns of connections of FPL to the river is essential in maintaining the ecological functioning of floodplains (Townsend and Walsh, 1998). Long-term analysis, taking into account the dynamics of river stages in the whole range of changes, allows identifying the main factors responsible for the duration and

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frequency of connection of the lakes to the parent river (Benke et al., 2000; Tockner et al., 2000, 2002).

We hypothesized that the frequency and duration of FPL functional periods result from inter-zonal (local) conditions (topography of the lake catchment expressed as Limnological Effective Rise (LER). Moreover, it was assumed that confluent lakes (connected upstream) were most frequently connected to the Bug River due to the distance from the river bed and the fact that they are fed consequently with the inclination of the river valley.

2 Study site

The study area was a fragment of the left (Polish) fraction of the Bug River valley, between distinct narrowings of the valley (gorge-like sections) near Dorohusk village in the south and Włodawa in the North (Fig. 1). The study was performed on a total area of 75 km^2. The Bug River is a meandering river in the study area. Its average multi-annual discharge amounts to 52.1 $m^3 s^{-1}$ in Dorohusk, and 56.0 $m^3 s^{-1}$ in Włodawa, while the long-term water level amplitude is approximately 450 cm. More than 70 floodplain lakes are located in the area under study, and the functional periods were observed in 20 of them. The FPLs were small and usually shallow (Table 1). Majority of the lakes do not have a name, due to the peripheral location. Symbols that have been used in this paper to identify the lakes refer to the section of the valley in which the lake is located, while numbers show compliance with the river course. The division of the valley into fragments was based on the existence of points of osculation of the river bed and the higher terrace. The studied lakes represent all hydrological types distinguished in the Bug River valley – confluent, contrafluent, contrafluent–confluent and profundal – and three types of origin – oxbow, avulsion and inter-levee (Dawidek and Ferencz, 2012).

3 Material and methods

3.1 Archive materials

Daily water levels of the Bug River from Dorohusk and Włodawa gauging stations over the period of 1952–2013 water years were used to determine the frequency and duration of the lakes functional periods (PF and LF). The data were collected by the Institute of Meteorology and Water Management in Warsaw. The hydrological year is counted in Poland as 12 consecutive months from 1 November to 31 October. The amount of precipitation 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 the lakes located in Orchówek Sobibór and Wołczyny Bug sections; the amount recorded at the Hańsk station was applied to lakes located at the Zbereże and Stulno sections of the valley and the amount recorded at the Dorohusk station was adopted for the lakes located in Wola, Uhruska and Dorohusk sections. The index of precipitation similarity for the FPLs under study was used to analyse limnophases and potamophases. The index considered two years: both the preceding and the following year of the year under consideration.

3.2 Field research

Field measurements were carried out over the period of 2007–2013 water years. Hydrological mapping included identification of crevasses that connect floodplain lakes with the parent river, determination of direction of water flow and the identification of each lake water distribution. Research of water distribution was performed during the spring potamophase periods. Current meter Nautilus 2000 was used to determine the direction of the flowing water.

Bathymetric measurements were carried out using ultrasonic probing of FPL basins, using echo sounder (depth measurement) and the method of satellite positioning with a Global Positioning System (GPS) receiver. Weight method (probe weight fixed into fiberglass tape) was included in winter and in periods when the lake bottom was intensively overgrown by macrophytes. Shoreline points, corresponding to the lake basin repletion, were recorded in the field using GPS Garmin. Bathymetric parameters of lake basins and hydrological distance from the Bug River bed were calculated using Didger software.

The starting point for determining the length and duration of floodplain lakes functional periods is to determine the value of Limnological Effective Rise (LER). Although this concept has not been previously recognized in the literature, many studies indicate the role of catchment topography of the FPL in connectivity between the river and its floodplain (Hughes and Rood, 2001; Amoros and Bornette, 2002). LER is a measure of water excess over river point bar (Fig. 2). The height of the layer (water level which guarantees the potamic feeding of an floodplain lake) is measured on a glyph of input crevasses. LER is usually given in centimetres.

The frequency of occurrence of events is the ratio of the number of events (n) in a given class interval to the total number of events N, n/N. It may be expressed in absolute numbers or percentages. Functional periods (PF and LF) of each FPL were classified based on their length into eight classes: 0–7, 8–30, 31–90, 91–182, 183–365, 366–730, 731–1460 and over 1461 days. The frequency of occurrence was analysed over the 62 year period on this basis.

The duration of the functional periods was understood as the total continuous length of the phenomenon (in days) over the time period under study. Relative methods have also been applied to analyse the frequency and duration of limnophases and potamophases. Described in the literature, Fluvial Connectivity Quotient (FCQ) (de Neiff et al., 2006; Behrend et al., 2009) was calculated as per Eq. (1). FCQ values used in the statistical analysis were the average values of the study of 62 water years.

$$\mathrm{FCQ} = \mathrm{LF} \times \mathrm{PF}^{-1} \tag{1}$$

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where FCQ is the Fluvial Connectivity Quotient, LF the limnophase (days) and PF the potamophase (days).

Potamophase Duration Index (PDI) was calculated for each water year from the following equation:

$$PDI = PF \times (LF + IN)^{-1} \quad (2)$$

where PDI is the Potamophase Duration Index, PF the annual duration of potamophase (days), LF the annual duration of limnophase (days) and IN the annual duration of inundation (days).

A variability index (VI) of functional periods in the study period was also calculated (Eqs. 3 and 4).

$$VI_{LF} = (62 \times LF) \Big/ \sum LF \quad (3)$$

$$VI_{PF} = (62 \times PF) \Big/ \sum PF \quad (4)$$

where VI_{LF} is the variability index of limnophases, VI_{PF} the variability index of potamophases, PF the annual duration of potamophase (days), LF the annual duration of limnophase (days), $\sum LF$ the total duration of limnophases in the study period (days) and $\sum PF$ the total duration of potamophases in the study period (days).

An index value of 1 means complete similarity to the long-term average values of the phenomenon; index values above or below 1 indicate an increase or decrease in the length of the functional phase in comparison to the average of 1952–2013 period, respectively.

The double-mass curves were used to evaluate the uniformity of the genetic relationship between the duration of LF and PF. The inflection points indicated the hydrological year in which the relationship has changed. PCA was used to determine the variances in a set of floodplain lakes under study. Application of PCA resulted from the linear structure of the data, confirmed by detrended correspondence analysis (DCA) analysis.

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4 Results

4.1 Terrain and climatic conditions

Terrain conditions that shape limnetic functional periods were limited to the Bug River discharge analysis in two profiles: the opening (Dorohusk) and closing (Włodawa) study areas. Flow characteristics showed clear seasonal, annual and long-term variations. The hydrograph of multi-years' average flow of the Bug River was typical for lowland rivers, and showed a clear spring and a second, smaller increase in discharge in the summer. Long-term average value of the specific discharge amounted to 3.88 $\mathrm{L\,s^{-1}km^{-2}}$. An important factor influencing the frequency and duration of the functional periods of floodplain lakes is the quantity and distribution of atmospheric precipitation. The study period of 1952–2013 was characterized by pronounced variability of atmospheric supply in each year and within a year. The sum of annual precipitation ranged from 377 mm in the year 1776 in Włodawa gauging station to 761 mm in the year 1970 in Dorohusk. The average annual precipitation during the study period amounted to 650 in Włodawa, 670 in Dorohusk and 680 in Hańsk.

The distribution of average monthly precipitation showed a prevalence of atmospheric supply in the warm season over the cold one (Dawidek and Ferencz, 2014). Torrential rains occurred irregularly, usually in the summer months (June–August). The longest periods without precipitation were also observed in summer. Values of the difference between the precipitation sum of two years (calculated before and after the current year) and the year under consideration varied significantly, within the range of −300 to 300 mm in the case of backward similarity (past years), and from −280 to 350 mm in the case of forward similarity (following years). Three distinctive periods were observed in the temporal distribution of such defined precipitation similarity: first until 1981, second until 1996 and third until 2013 (Fig. 3).

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4.2 Functional periods of the floodplain lakes

A knowledge of the structure of functional periods of FPL is of fundamental importance in understanding their functioning. Potamophases and limnophases were assigned into classes due to their duration, over the study period of 62 years. The frequency of occurrence of LF demonstrated a large variation within the distinguished classes, from zero to almost 60 episodes.

Short (8–30 days) and medium-length (183–365 days) limnophases occurred in the Bug River valley most frequently. The number of observations in each class enabled to distinguish three groups of lakes with a strong structural similarity. The first group (six FPLs) of lakes was characterized by the superiority of occurrence of short limnophases, from one week to one month (Fig. 4a). The frequency of the other classes showed no clear dominance in this group, and it is worth emphasizing that very long limnophases occurred only in this group of lakes. The second group of lakes (seven FPLs) was characterized by the highest frequency of the limnophases that span from half to one year (Fig. 4b). A number of observations within the range of the other classes were also not regular in this case. In four lakes in this group (DO7, WO2, ZB3 and WO3) limnophases shorter than a month also occurred more frequently. In remaining three lakes in this group (ST5, OR1 and ZB1), the frequency of longer limnophases (31–90 days) was significant (Fig. 4c). In case of every lake in this group, limnophases longer than four years were observed in the study period. The third group of floodplain lakes (seven water bodies) were the lakes in which no tendency in the frequency of limnophases occurrence was observed.

The potamophases frequency in the FPLs, in relation to limnophases, was higher, but its volatility implemented only four classes. Three groups of lakes have also been distinguished based on the frequency of PF occurrence. Despite the general dominance of the frequency of short potamophases (from one week to one month), the first group of lakes (eight) consisted of water bodies with the most frequent occurrence of potamophases lasting from 8 to 30 days (Fig. 5a). In this group, potamophases with duration

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of less than a week were more likely than those with a duration of 31–90 days. The second group was characterized by the inverse occurrence of potamophases lasting 0–7 and 31–90 days, in relation to the first group (Fig. 5b). The third group consisted of the lakes in which, unlike in the other groups, potamophases with a duration of 8–30 days were less than the sum of the remaining classes (Fig. 5c).

The analysis of the frequency of functional periods was supplemented with the analysis of the duration of the periods. The dynamics of the occurrence of the phenomenon, which was the derivative of the water input, and from its duration, was also determined by terrestrial conditions of the catchment. A general similarity of process was observed in most water bodies. Four out of 20 floodplain lakes showed distinctiveness in the duration of limnophases and potamophases (Fig. 6). Lake ZB1 showed pronounced dominance of LF periods, while in lakes ZB3, WO2 and DO6 a relatively longer duration of PF was recorded. The average ratio of the duration of the two phases – limnetic and fluvial – revealed the prevalence of limnophases. Double-mass curves enabled to determine the four periods of dominance of one of the functional phases. Limnophases lasted longer than potamophases until 1965. The trend has been reverse from 1962 to 1982, and the restoration of limnetic water resources (after a decade of deficit) occurred on the basis of increased fluvial input. The next 15 years, until 1997, were a period of extremely long LF and increase in the FPLs' role of supply from their own catchments. The last 15 years were characterized by a renewed increase in the importance of fluvial supply.

Short periods modifying this general scheme of the duration of functional periods occurred in a few floodplain lakes. However, it did not affect the existing trend. A very prominent feature of the durations of LF and PF was the long periods of superiority of either phase. A variation in the duration of the LF and PF in relation to the long-term average value was also analysed. Values greater than 1 occurred when the phase in the particular year was longer than its average duration during the study period, while less than 1 indicated that it was shorter. Until 1965 a large variation in the duration of LF in majority of lakes concerned values above the perennial average (VI_{LF} values

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were below 1). Years from 1965 to 1982 were the period of exceptional variability of the duration of limnophase (Fig. 7a). VI_{LF} ranged from 0.3 to 1.5. It was the period in which multi-directional trends of LF duration occurred. The 15 year period from 1982 to 1997 was characterized by resemblance of limnophase diversity to the first period, with an insignificant shift of the phenomenon in slightly higher registry. After 1997, there were again multi-directional changes observed in the general trend. The values were perennial averages.

VI_{PF} variability was almost a mirror image of VI_{LF} variability due to the fact that LF and PF are complementary (Fig. 7a and b). However, the index varied in a smaller range than VI_{LF}. Periods of decline in the importance of potamophases showed lower dispersion, while with the increase of the PF duration variability of the index increased (Fig. 7b).

In the study, PCA explained the relation between the origin of the functional period and the hydrologic conditions of the river valley. Indirect ordination method used in the analysis helped organize the structure of the hydrological types of FPLs dependent on a specific factor. The main direction of changes, which, to a great extent (62.7 %) explained variation of the study lakes, was their morphometric characteristics (first axis). The maximum depth of lake basins, represented by the longest vector, has been interpreted as the environmental gradient responsible for diversity of a data set (Fig. 8). The second axis, corresponding to the internal differentiation within the hydrological types of lakes and the distinction between profundal and contrafluent–confluent lakes, was difficult to interpret (explained 35.8 % of the variation). The gradient represented by this axis only indicated an increase in the role of the lakes surface.

5 Discussion

The processes of spatial and temporal variability of functional periods, which have been addressed in the paper, form the basis for biogeochemical and ecological research, for conservation and management of natural resources (Junk, 1997) and for analysis of the environmental impact of channels modifications such as dredging rivers or changes in retention capacity (Hamilton, 1999). Exchange of water, sediments, ions, organic matter as well as fauna and flora occurs in potamophase period between the river and the floodplain lakes (Junk et al., 1989; Thoms, 2003; Bunn et al., 2006). Lateral connectivity between the parent river and its floodplain, rich in FPLs, is known to be crucial for the functioning and integrity of floodplain–river ecosystems (Amoros and Bornette, 2002). Periodic flooding changes the proportion of suspended and dissolved components in water by altering its physicochemical conditions (Melack and Forsberg, 2001) and the water characteristics and its dynamics are crucial to understand the processes and dynamics that occur between terrestrial and aquatic ecosystems (Melack and Fisher, 1990; Moreira-Turcq et al., 2003; Aufdenkampe et al., 2007; McClain and Naiman, 2008; Almeida and Melo, 2009). Flooding impulses periodically modify the terrestrial environments of the floodplain into aquatic environments.

Determination of LER was a key factor in qualifying the frequency and the duration of the functional periods of floodplain lakes. The relationship between the river water level and the flooding of the floodplain has been previously documented for tropical rivers, with predictable flood regimes. A linear relationship between monthly estimates of inundated area and flood stages was described for Pantanal wetlands of South America (Hamilton et al., 1996). The overall distribution of potamophases and limnophases in the 62 year study period showed a relationship with the fluvial dynamics (water stages and discharge) of the Bug River. The variability of limnophases and potamophases, observed for individual lakes, depended on two factors, lakes' supply and the morphometry of their basin. The more unstable the supply and the lower the lake basin retention capacity, the higher the variability. Affonso et al. (2011) explained the spatial variability between the hydrological phases with several factors, including the volume of water, the main channel of the river input, lake morphometry and a type of connection with the river.

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The lakes under study individually responded to the input in the form of potamic supply, precipitation or snowmelt. The reaction rate depended on the condition of the geographical environment of the catchment area.

Floodplain topography, which is a catchment of FPLs, is a key factor in the duration of potamophases (Ganf et al., 2010; Karim et al., 2012). Studies have shown that lake basins characterized by high retention capacity show a relatively small variation of limnophases, and those with low retention of lake basins are characterized by a high variability of LF periods. The functional periods tend to show a cyclical nature of occurrence. This recurrence is related to the nature and intensity of atmospheric supply of the inundated area (Karim et al., 2012).

Adjusting of biotic environment for quantitative (excesses or shortages of water) and qualitative (impact of hydro-chemically different river waters and water drained from their catchment (Taniguchi et al., 2004; Ahearn et al., 2006; Paidere et al., 2007)) aquatic conditions (Lewis et al., 2000; Shin and Nakamura, 2005; Luef et al., 2007) is a result of long-term superiority of one functional period. The reaction of the FPL ecosystem to the short-term dynamic changes (of short duration) is insignificant, even with a large number of episodes occurring.

In complex conditions, for example gorge-like valley sections, where catchments generally have diverse topography, part of the water that infiltrates to FPLs may be involved in the deep-circulation process and supply only to the deepest lakes. Groundwater (apotamic origin) for shallow lakes may be simultaneously drained by deep lake basins. Assuming a similar quantity of atmospheric input in the catchment basins of the lakes under study, a specific response has been expected: shortening of limnophase due to river inflow.

Under the conditions for the drainage of small lake basins, an impulse of effective infiltration is usually too weak and does not affect the formation of potamophase. This confirms earlier results presented by Levashova and others (2004). The results of this study showed that local precipitation in the lake catchment was insufficient for the tran-

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sition from the deep limnophase into the potamophases; extra-zonal precipitation in the upper Bug River catchment was essential to initiate the process.

The longest limnophases occurred during periods with lack of atmospheric precipitation when a recession of groundwater recharge and systematic increase of water resources in the catchment were noticeable. The conditions changed radically only when intense precipitation was observed in the upper part of the Bug River catchment (the area above the research study). The highest dynamics in the examined multi-year period was observed in case of short and very short functional periods, lower dynamics was observed in medium-length phases, while the dynamics was lowest in both long limnophases and potamophases. A period of the highest fluctuation from hydrological point of view occurred most often in the middle range of high water levels (HWL) of the parent river (Tockner et al., 2000; Benke, 2001). In periods of very high water stages (close to overbank), even small precipitation impulse usually initiates fluvial supply into floodplain lakes. Such a pattern occurred seasonally, after a period of high discharge due to spring snowmelt, or during the wet summer months. After the parent river stages had dropped into the middle range, limnophases were durable, even in the presence of an intense local precipitation.

A simultaneous occurrence of favourable conditions in two groups of factors decided the duration of extremely long functional periods in Bug River FPLs (limnophases lasting continuously over 1000 days and potamophases over 100 days). The following factors were responsible:

- External conditions (outside the lake catchment): meteorological macro-scale conditions, which directly affected the amount of water in the river beds, which was confirmed by PCA
- Internal conditions of FPL catchments: catchment topography, which may modify (favour or limit) climate impact and inundation processes, due to levee height, crevasses overgrowth, beaver dams and river bed shape (Van de Wolfshaar et al., 2011).

The results partially confirmed the hypothesis that the frequency and the duration of functional periods of FPLs are determined by local conditions. In addition to the catchment topography, the duration and frequency of potamophases and limnophases are also affected by precipitation in the upper catchment of the parent river. PCA analysis showed that higher the number of confluent and profundal lakes, the deeper the lake basins, which is favoured by frequent connection of the lakes to the Bug River. This confirms the earlier hypothesis. In such conditions, there are relatively highest lake basins capacities. It directly affects and determines the conditions for the creation and maintenance of the functional periods.

With the increase in contrafluent–confluent and contrafluent lakes, the depth of lake basins and consequently the lake basin–retention capacity clearly decrease. Therefore, the inertia of the functional periods is low. Documented in the paper, the relationship between VI_{PF} and the hydrological distance from the parent confirms the thesis of Van de Wolfshaar et al. (2011) that with the increase in the length of water input channels, the lake isolation increases (long, deep limnophases). At the same time, the hydrological condition of the lake, expressed by the volume and maximum depth of the lake basin, shows a significant correlation with the FCQ.

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Table 1. Selected characteristics of the study lakes.

No.	Symbol	Type	φ [° N]	λ [° E]	A [ha]	V [dam^3]	L [m]	W [m]	D [m]
1	OR1	Ctr-c	51.5309	23.5711	8.3	62.2	1469.4	100.0	2.6
2	OR7	Ctr-c	51.5162	23.6134	2.5	17.7	681.4	84.7	2.7
3	ZB1	Ctr-c	51.4232	23.6834	5.0	47.0	714.3	129.2	4.9
4	DO8	Ctr-c	51.1878	23.7843	1.2	28.4	582.6	57.8	4.1
5	OR9	Con	51.5103	23.6127	1.1	10.8	384.4	56.5	3.6
6	ST6	Con	51.3699	23.6623	3.1	21.7	603.6	83.7	5.2
7	ST5	Con	51.3726	23.6669	3.4	27.3	852.7	106.5	6.8
8	DO7	Con	51.1884	23.7753	4.7	91.5	681.2	115.7	6.8
9	ZB3	Ctr	51.4110	23.6960	1.5	11.2	450.9	63.4	3.0
10	ST3	Ctr	51.3710	23.6741	3.0	18.8	910.2	66.4	2.1
11	WU10	Ctr	51.2623	23.7197	0.1	4.9	234.9	85.7	3.2
12	WU11	Ctr	51.2624	23.7198	0.2	0.4	228.3	66.3	2.8
13	ST8	Ctr	51.3514	23.6515	2.1	24.9	569.4	122.1	5.9
14	SO7	Ctr	51.4866	23.6550	0.4	1.5	275.3	19.7	1.0
15	SO8	Ctr	51.4872	23.6566	0.2	0.4	118.0	22.4	0.7
16	WO2	Ctr	51.4408	23.6728	1.0	4.6	512.3	27.3	2.1
17	WO3	Ctr	51.4381	23.6730	0.8	7.5	215.2	69.6	3.9
18	WU2	Prof	51.3272	23.6306	5.5	88.9	810.5	158.6	10.3
19	DO5	Prof	51.1972	23.7625	0.9	101.0	1046.7	86.5	8.6
20	DO6	Prof	51.1905	23.7710	0.7	33.6	203.4	94.9	7.1

φ: latitude; λ: longitude; A: area; V: volume; L: length; W: width; D: depth

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Figure 1. Study area. Valley fragments: OR – Orchówek, SO – Sobibór, WO – Wołczyny, ZB – Zbereże, ST – Stulno, WU – Wola Uhruska, DO – Dorohusk.

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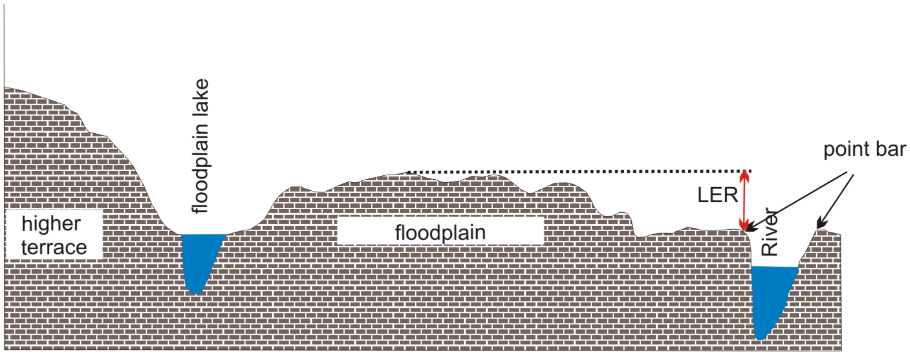

Figure 2. Limnological Effective Rise (LER).

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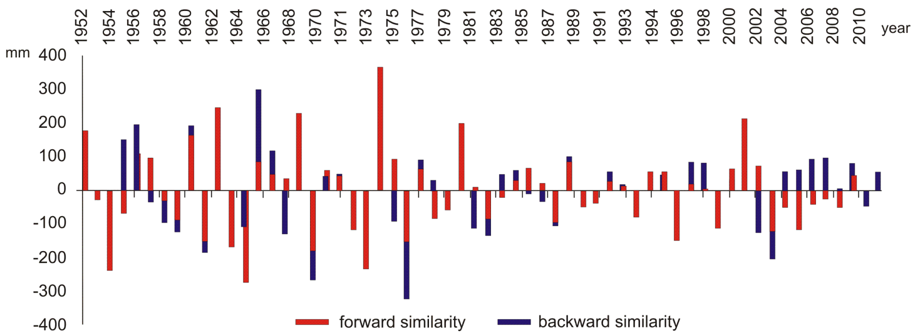

Figure 3. Temporal variability of precipitation similarity indices in the study period.

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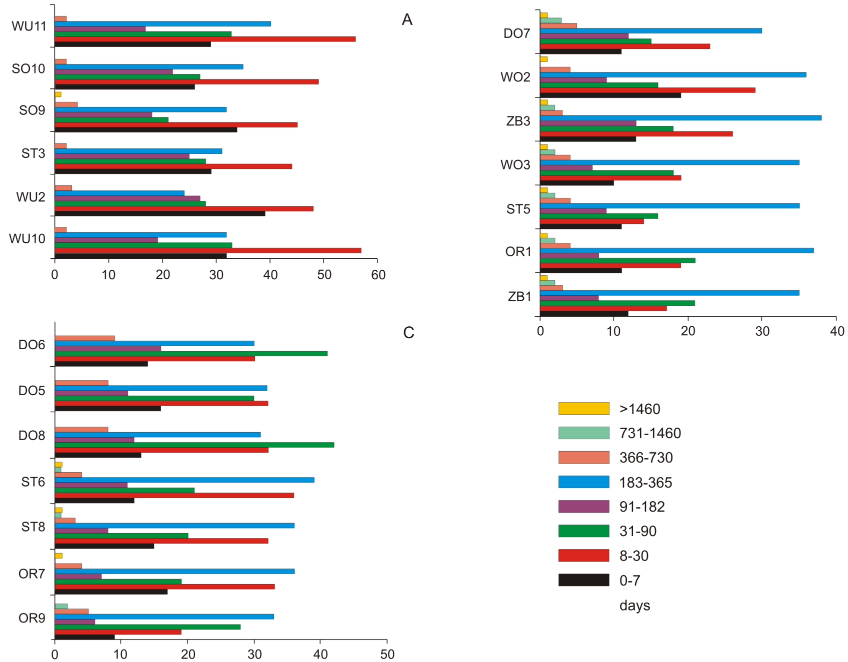

Figure 4. Frequency of limnophases occurrence in the study floodplain lakes: **(a)** – first group, **(b)** – second group, **(c)** – third group.

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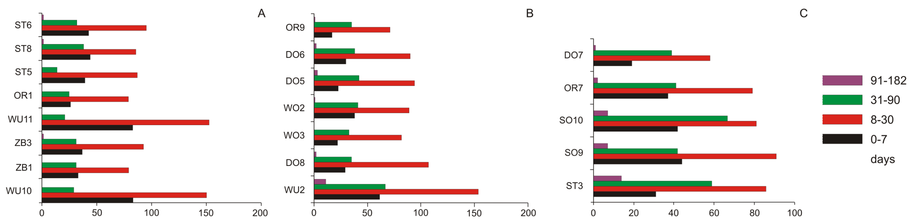

Figure 5. Frequency of potamophases occurrence in the study floodplain lakes: **(a)** – first group, **(b)** – second group, **(c)** – third group.

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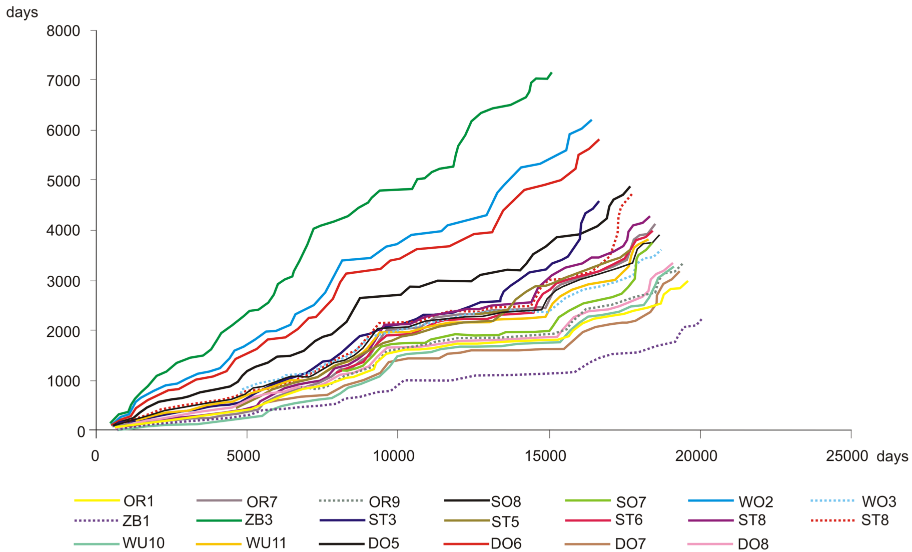

Figure 6. Double mass curve of limnophases and potamophases duration in the study flood-plain lakes.

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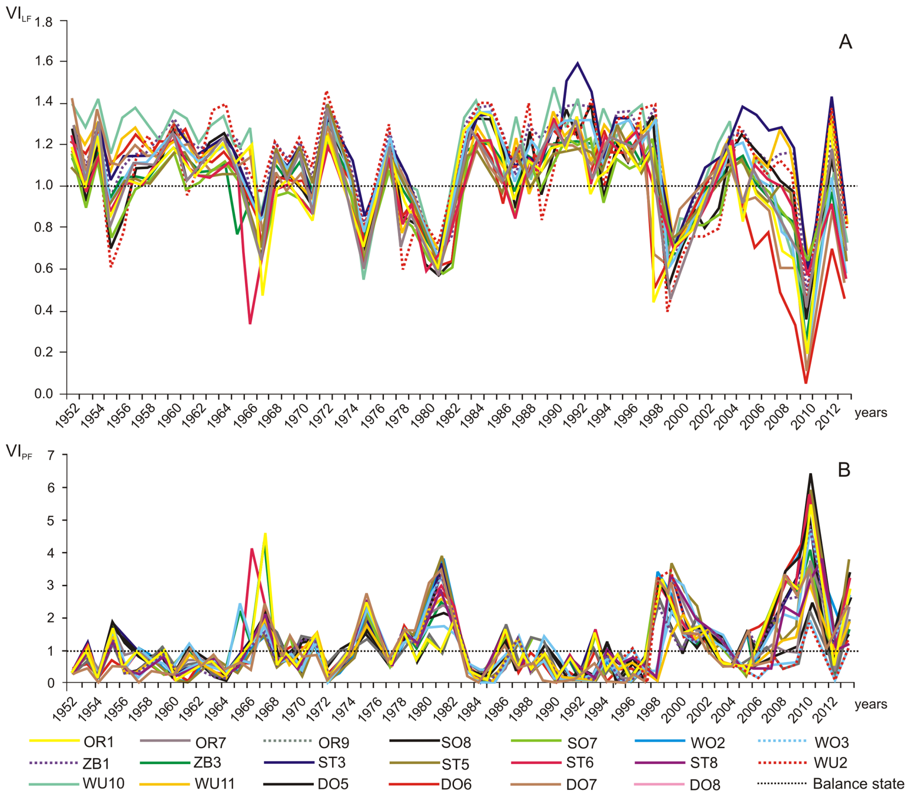

Figure 7. Variability index of **(a)** – limnophases and **(b)** – potamophases in the study period.

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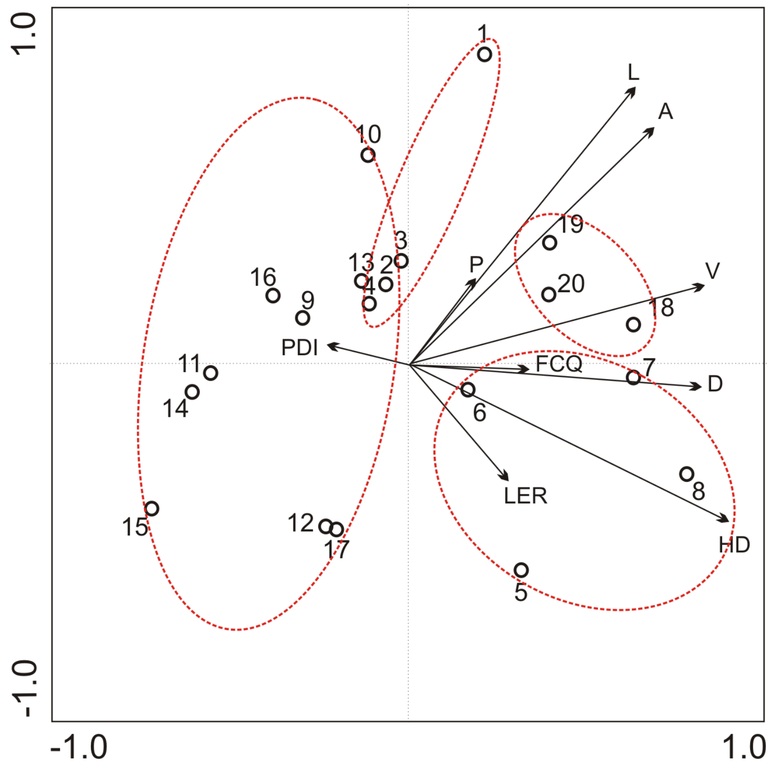

Figure 8. Principal component analysis of the floodplain lakes. P – precipitation, L – length, A – area, V – volume, D – depth, HD – hydrologic distance from the parent river, LER – Limnological Effective Rise, PDI – Potamophase Duration Index.

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