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HYDROLOGICAL PROCESSES IN THE RIVERINE SYSTEMS, THE ORIGIN AND CLASSIFICATIONS OF FLOODPLAIN LAKES

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Abstract

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Fluvial lakes are a very important part of the natural or quasi-natural river valleys. Although their origin is usually identified with the process of cutting off the meandering neck, there is also a large number of other processes responsible for floodplain basin creation. The first classifications of the floodplain lakes were very simple. All the lakes were considered as a homogenous group of oxbows, and their division was mainly based on shape. Hydrological studies of floodplain lakes have been more popular since 1990, with two phases of the lakes functioning being pointed out; inundation or potamophase and isolation or limnophase. The next step in floodplain lakes research was the division into hydrological types; evaporation-dominated, flood-dominated, and exchange-dominated. Moreover, those types of confluent, contrafluent or profundal lakes were distinguished with regard to the supply direction (with reference to the river). A hydrochemical classification of floodplain lakes was published in 2005. Three types of lakes, extra-zonal, inter-zonal and mix-zonal, and three kinds of each type were distinguished. Taking into consideration all the processes in the river valleys, a few feedback loops can be indicated, regardless of the climatic zone or intensity of the processes.

Key words: oxbow, lakes typology, meandering rivers, hydrology, inundation

Introduction

Fluvial lakes play a very important sozological role, by accumulating both mineral and organic substances (Koc et al., 2009). Ecological advantages of floodplain inundation were presented in the studies of temperate river systems (Drago, 1976; Junk et al., 1989; Bayley, 1995; Tockner et al., 2000). The high seasonal dynamics of lakes parameters, including bathymetry, water chemistry and trophy from river inundation, form the main characteristics of floodplain lakes (Melack, 1984; Welcomme, 1985; Forsberg et al., 1988; Marsh, Hey,

1994). All the features mentioned above determine typological diversity of floodplain lakes. According to division criteria, several different types of lakes can usually be distinguished. Lakes originating from fluvial processes are some of the most popular water bodies in areas with natural or quasi-natural river valleys (Garcia de Emiliani, 1997; Lewis, 2000). However, knowledge concerning floodplain lakes is usually poor, so that vary disordered terminologies concerning these lakes and rare hydrological investigations and make comparison of fluvial lakes very difficult. In addition, the alternative usage of terms from biology, geo-morphology and geography can cause many misunderstandings.

The aim of this study is to balance and compile information regarding river lakes.

Materials and methods

The major group of materials used in this study was papers concerning climatically various river systems. Since most river valleys are subject to human activity, fluvial, morphological, hydrochemical and hydro-biological aspects were analyzed in order to quantify the main factors determining floodplain lakes heterogeneity. A representative group of temperate zone floodplain lakes water bodies located in the Bug river valley, one of very few large, quasi-natural European rivers in Eastern Poland was chosen. A functional analysis of lake basins led to the construction of uniform floodplain lakes classification.

Results

The definition of a floodplain lake

A floodplain lake includes every inland water body, whose basin originates from fluvial processes, and its limnological functioning derives from irregular, but periodical limnophases and potamophases. Floodplain lakes have the following various names and definitions: a geo-morphological term "neck cut-off" (Fisk, 1947; Camporeale et al., 2008; Constantine, Dunne, 2008), oxbow lake (Wolfe et al., 2006; Wren et al., 2008), fluvial lake (Reavie et al., 2005; Frenette et al., 2003), or less often "river lake" (Wojciechowska et al., 2005), hydro-biological "limnocren" (Czachorowski et al. 1993; Khmelewa et al. 1994), hydrological "floodplain lake" (Tockner et al., 1999; Hamilton et al., 2004; Okogwu, 2010), are often used in the studies. There are also many other terms, such as mort lake (Pavlova, Dorozhkina, 2002), and crescent lake, which are both used to describe the same type of lake. All the above terms are inaccurate and do not define the functioning of a lake. A vivid example is in the "crescent lake", which means both floodplain and an eolian lake in a deflation niche. There is also a diversity of local floodplain lakes terminology: in Australia these are called *billabongs*, (Nielsen et al., 2002) bayous in the USA (Farabee, 1992), *jama* in Poland or Ukraine, starica (*старица*) in Russia. Floodplain lakes of Central Europe are usually called after the river they originate from; Labe river – Labištie (Czech Republic), the Vistula river – *wiślisko* or Bug river – *bużysko* (Poland). The lack of one clear typology of floodplain lakes and lack of water body full identification suggest homogeneity of this group. The river valley and

especially its floodplain processes are dynamic. The intensity of the changes is a result of geological structure, relief, and also the morphology and type of the river, climatic conditions and vegetal cover. In order to compile floodplain lake terminology, a simple division based on the lake's origin and functioning is presented in Fig. 1.

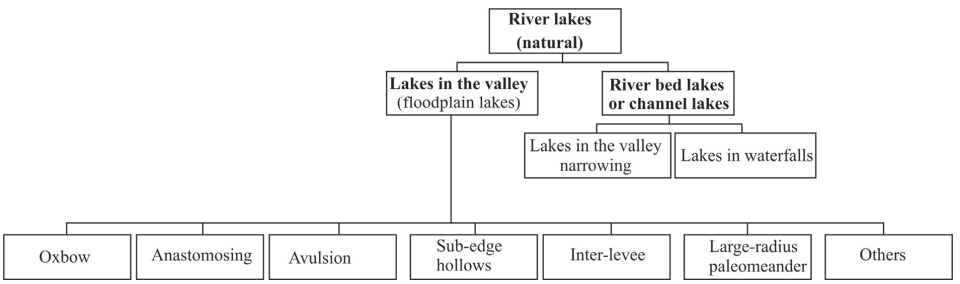

Fig. 1. A division of lakes originated from fluvial processes.

Artificial dam reservoirs are a distinct group of water bodies which cannot be classified as lakes, according to the earlier mentioned definition, due to their anthropogenic origin. These water bodies, however, are located in the river valleys, and the human activities of water distribution, flushing time, and water circulation play a significant role in the reservoirs' physical, chemical and biological functioning.

Functioning of the floodplain lakes

A periodic occurrence of potamophase and limnophase is the main characteristic feature of the floodplain lakes. The pronounced seasonality of these lakes functioning was presented in many studies (Sioli, 1984; Melack, 1984; Hamilton et al., 2002). However, the duration and time of phase occurrence depend on the climatic zone. Many authors identified four cyclical phases: filling, through-flow, drainage and isolation (Drago, 1989; Hamilton, Lewis, 1990; García de Emiliani, 1997). Other studies established a division into two phases: inundation or potamophase and isolation or limnophase (Lesack, Melack, 1995; Schemel et al., 2004; Heng et al., 2006). During the limnophase, in-lake processes determine the lake features. The lake is supplied by the catchment area, and this shapes the type and intensity of hydro-chemical and hydrological processes. A significant correlation between physical-chemical parameters of a lake and its basin can be observed during the potamophase. The catchment area expands at that time and it is equal to the river catchment up to the channel supplying the lake basin. Floodplain lakes can lose their identity completely during inundation, becoming only a hollow in the floodplain. The natural physical processes that determine floodplain lakes functioning depend on duration and intensity of potamophase

and limnophase. The Fluvial Connectivity Quotient (FCQ) can be calculated from the phase duration. This equation establishes duration of connection to the river and the number of days when the lake is disconnected. A fluvio-dynamic and hydraulic river power decides the accumulation or erosion processes of mineral substances in the lakes' basins, and these are also the main factors shaping thermal, optical and oxygen water-conditions. The lake's origin is connected to the fluvial processes and it determines the water distribution and the quantity of the basin's supply. The great majority of floodplain lakes become flow-through water bodies during the potamophase. However, water circulation is heterogeneous. Lakes can be hydraulically connected to the river at the upstream end, which favours flushing of lakes' water, or at the downstream end, through a crevasse. This downstream connection causes a longer period of lake isolation and maintains specific physical-chemical parameters of lake waters.

This type of supply favours physical-chemical autonomy of lake waters. Higher supply is usually the gorge vicinity due to the underground seepage from the surrounding hydro-geological unit. Both the hydro-chemical and hydro-biological qualities of the lake waters is determined by the direction and intensity of lake alimentation. Floodplain lakes are hydro-biologically dependant on the course of a river. Although they are absent in the *crenal* and *rhitral* (upper sections), they occur in *potamal*. A majority of floodplain lakes are observed in *metapotamal* and *hypopotamal*. The processes of fluvial lake functioning can be explained using Liebig's and Shelford's law. This analysis defines excess and deficiency of factors which can limit aquatic organisms. Population growth can be limited by both biotic and abiotic factors, and the limit to tolerance defines the range of intensity of these factors for population survival. While eurobionts easily adjust their tolerance levels to environmental changeability, stenobionts possess a very low tolerance level.

Typologies of the floodplain lakes

Holistic lakes classifications, such as genetic, trophic, thermal and mictic, treat a group of floodplain lakes heterogeneously (Hutchinson, 1957; Drago, 1976; Lewis, 1983; Häkanson, 1981). These classifications are based on the general processes of lake-basin creation and they consider all floodplain lakes as oxbows. All existing typologies are insufficient for floodplain lakes, since final results usually lead to the domination of one category, while the group of lakes located in the river valleys is distinct from other lakes, and also within itself. Therefore, accurate characterization of floodplain lakes is only possible when all the hydro-geological, hydrological, and hydro-chemical information is compiled and considered.

The processes of lateral erosion and abandoning meanders have been fully investigated since the beginning of the 20th century (Davis, 1903), while studies of floodplain lakes were only supplementary to wider and complex valley and river investigations (Brigham, 1892; Davis, 1903). The necessity of a division within fluvial lakes was noted a long time ago.

According to Weihaupt (1976), for a lake to be classified as a floodplain lake, it must: (a) be located on a floodplain and shows some apparent relationship to the major stream, (b) be located within a distance of fifteen stream widths of the major stream, (c) contain water,

(d) include at least one segment with a crescent-shaped channel (called the "fundamental component"), (e) have a size of the same general magnitude as the major stream, and (f) be independent of other topographic influences, which means that each oxbow lake must be free-standing. Attempts at hydrological classifications, following Weihaupt requirements, were made during the late 20th century. The simplest floodplain lakes typologies were then based on shoreline shape and development. Three types of lakes were distinguished in terms of oxbow lakes morphometry (Weihaupt 1977). The first classification was based on the degree of complexity, and consisted of the three categories: simple oxbow lakes, compound oxbow lakes, and complex oxbow lakes. The second classification was based on the degree of closure of oxbow lake limbs, and also consisted of three categories: open oxbow lakes, normal oxbow lakes, and closed oxbow lakes.

A very interesting approach was the division of floodplain lakes based on the main direction of water circulation. In evaporation-dominated lakes, there was a dominance of vertical water exchange while in flood-dominated ones, the horizontal exchange prevailed. Hamilton and Lewis (1990) considered the ratio of length and width of the water body as a main factor in floodplain lake classification during the limnophase. Two types of lakes were distinguished based on the ratio value: channel lakes, with short retention time, where the ratio was higher than 5, and dish lakes, with a longer residence time and a ratio value lower than 5.

Six categories of floodplain lakes were distinguished by Chmiel et al. (2003) for the natural European Bug river. Lateral erosion favours creation and abandonment of meanders, within a meander belt, forming the youngest and most unstable part of the river valley. Abandonment of the meanders leads to oxbow lake creation, forming the youngest and most numerous type of floodplain lakes in the world. These lakes are usually shallow and are quite susceptible to degradation as a result of matter accumulation during the potamophase and its location in the river's proximity. European rivers underwent a phase of large-radius meander creation in the Vistulian and Holocene periods. The remnants of this phase are floodplain lakes which are old and distant from the river To improve rising waters flow, rivers can divide into many channels before the gorge section and where the valley widens. During most of the year, anastomosing channels are isolated from the river and function as floodplain lakes.

River slope declines after the gorge section, thus favouring the abandonment of long parts of the river channel, and creation of avulsion lakes which are diverse in terms of depth and area.

Levees form integral parts of the middle course of rivers, and the stagnant waters in lower separating levees create inter-levee floodplain lakes. These lakes characterize seasonal water level fluctuations by disappearing during drought periods and increasing several times in area during inundations.

In the valley sections where the floodplain and second terrace are separated by a pronounced edge, water stagnates in hollows at the foot of the higher terrace after inundations. The chained located shallow and oval floodplain lakes have been called sub-edge lakes.

The next most popular floodplain lakes in the tropics can be distinguished according to Drago (1989). These include: (1) inter-bar ponds, which are formed when a large chan-

nel stretch is dammed at its ends by fluvial bars or islands so that their surface is usually large and dentritic; (2) overflow ponds originate from uneven aggradations or degradation during floods and these are located in smooth depressions, near the main channel, and (3) annexation ponds are formed by the fusion of two or more water bodies, and their shapes can be sub-rectangular-elongated or dendritic.

The direction of water supply can also be a factor of hydrological division of floodplain lakes (Dawidek, Turczyński, 2006). When the direction of water-flow supply and the dip of the valley are identical, as in upstream connection, confluent floodplain lakes with high water exchange dynamics occur. In contrast, lakes with an active crevasse are supplied downstream and contrafluently (Fig. 2).

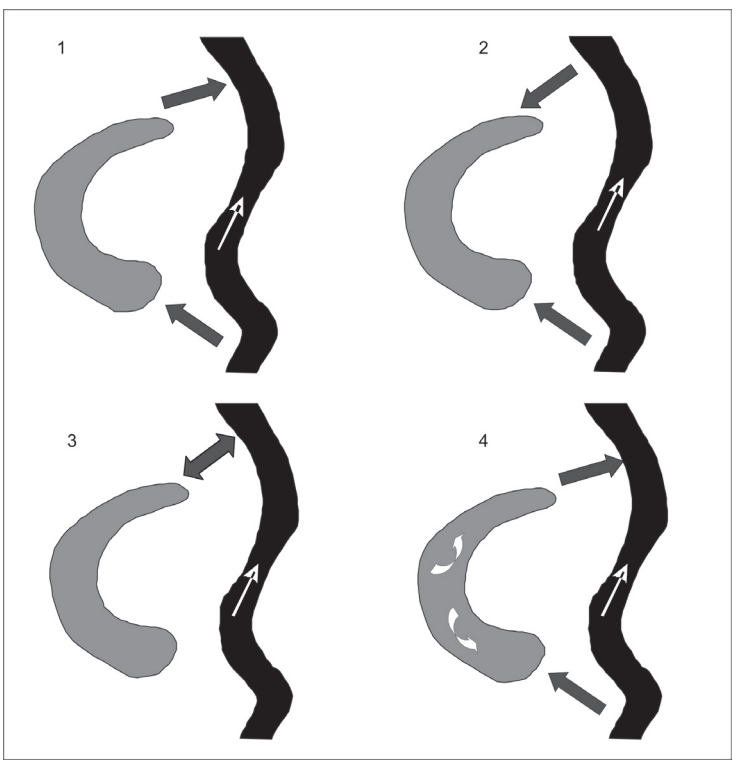

Fig. 2. Types of floodplain lake supply.
1. Confluent floodplain lake, 2. Contrafluent-confluent floodplain lake, 3. Contrafluent floodplain lake, 4. Profundal floodplain lake.

When a lake is supplied through two channels, autochthonic water is directed to the centre of the basin constituting a contrafluent-confluent floodplain lake. There are also confluent or contrafluent lakes which are supplied by underground waters. If the underground flow

is high enough to determine the water level during the limnophase stage, the lake is called profundal.

In-lake processes are shaped by hydro-physical factors plus hydro-chemistry of the floodplain lake catchment and the hydro-biology of its basin.

Lake water quality results from the location of the lake in the river valley and the availability of river waters, and this is reflected in lake eutrophication. According to Dawidek and Ferencz (2005), there are three kinds of lakes, and within each of these three further types can be distinguished, based on the catchment conditions and water quality.

Lakes situated in the river bed vicinity are called extra-zonal, where an intensive water exchange is observed during potamophase. Floodplain lakes situated at a long distance from the river bed and inundated only during periods of extreme river water levels are called inter-zonal, while transitional lakes are known as mix-zonal. Three types of lake may be distinguished dependent on the chemical parameters of the waters: (1) *maior* –where the water quality is determined by the condition of the catchment, (2) *minor* – where the water quality is influenced by anthropogenic pressures, and (3) *integralis* – where there is a high correlation between the composition of the lake and river waters.

Conclusion

Floodplain lakes remain the least known group of water bodies. Their investigation should be completed by the synthesis of both catchment and in-lake processes deciding on the lake's identity. Taking into consideration quantitative hydrological processes: the direction and duration of lake supply, or water exchange as a result of alimentation, an attempt at predicting qualitative conditions, such as water physical-chemical parameters, can be made.

The prime process that determines fluvial lakes is inundation. Alteration and duration of potamophase and limnophase result in a specific hydrological type of the floodplain lake. A value of Fluvial Connectivity Quotient (FCQ), understood as the ratio of lake volume to the value of the flow through the basin, shapes residence time.

Short residence time during the potamophase was stressed by Drago (2007), Hamilton, Lewis (1987), Schemel et al. (2004) and many others. Lake waters quality results from the direction and pace of water circulation. In natural or quasi-natural temperate rivers, floodplain lakes show specific periodicity, which can be observed over the longer time scale.

Regardless of climatic zones, the most popular water-bodies in the river valleys are:

- Flood-dominated lakes, with short residence time (usually confluent) and as a result of high mineralization in the water. Their presence in the Slave valley was observed by Sokal et al. (2008).
- The lakes which have a ratio of potamophase and limnophase duration typical for exchange-dominated lakes, where the residence time is longer than in lakes mentioned above (contra-fluent or profundal lakes). The concentration of dissolved solids in lake waters is lower than that observed in the river.

- Evaporation-dominated lakes with very long residence time, as in profundals, where water parameters are shaped by the catchment area. The range of fluctuations depends on hydro-geochemical conditions and human pressure.
- Evaporation-dominated lakes which have a moderate water residence time and high concentration of dissolved solids. Higher mineralization of lake waters compared to the river can result from rocks' susceptibility to chemical denudation, the evaporation of the dense water solution or from contamination.
- Flood-dominated lakes which have moderate water residence time. Concentration of dissolved solids varies here, dependent on the intensity of anthropogenic pressures and the quantity of underground supply.

Local and ambiguous definitions of floodplain lakes make it impossible to compare lakes located in different climatic zones. Unification of terms and strict typology supply the best solution to this problem.

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