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Beaver ponds and mill ponds. History and water retention function. The Polish Plain study

Abstract: This paper presents the results of studies on small-scale water retention in beaver ponds and mill ponds located within the Polish Plain in the catchments of the Brda and Wda Rivers. Findings regarding small-scale retention in the Holocene were based on geological surveys and archival materials in the presence of beaver ponds and mill ponds. Traces of Holocene and contemporary beaver colonisation in this area have been documented. We collected data on the location of mill ponds during various developmental periods of the millers' trade. The potential maximum retention in Holocene beaver ponds, contemporary beaver ponds and mill ponds was estimated and compared in both examined catchments at various stages of the development of the miller's trade. It was established that retention in mill ponds at the peak of the development of the miller's trade in the catchments of Brda and Wda was four times lower than the potential retention in beaver ponds during the pre-anthropogenic stage of the Holocene. Current small-scale retention in beaver ponds is variable and definitely smaller than natural and anthropogenic retention in the past. It did not compensate for the water loss associated with irrigation practices in this area.

Keywords: Holocene, small-scale retention, beaver ponds, mill ponds, catchment of the Brda, catchment of the Wda, North European Plain.

1. Introduction

The aggravating problems due to contemporary climate changes encourage a closer look at the growing water deficit and the protection of water resources. Reducing water loss by creating adequate conditions for small-scale retention is an essential aspect in Poland (e.g. Grygoruk, 2008; Grygoruk and Nowak, 2014). In natural landscapes, the retention of water in reservoirs and soil is a function of the geological structure, landform features, climate, and vegetation cover. In small elementary catchments in temperate forests, zone retention can be reinforced by the presence of natural baffles in riverbeds (dams formed by fallen trees and beaver dams) and man-made baffles (levees).

Following the retreat of the Pleistocene continental glacier from the North European Plain, the boreal forest landscape formed on fresh glacial sediments, with a share of deciduous tree species increasing with time. From the end of the Pleistocene, beavers were an integral component of successive generations of temperate forests. Their presence in the Holocene in areas situated in the contemporary territory of Poland has been documented by bone remains found in archaeological sites (Abłamowicz et al., 2008, Fig. 1). Over the past 10,000 years, beavers have become an essential element of the landscape, maintaining water retention in catchments. In river valleys, during the Holo-

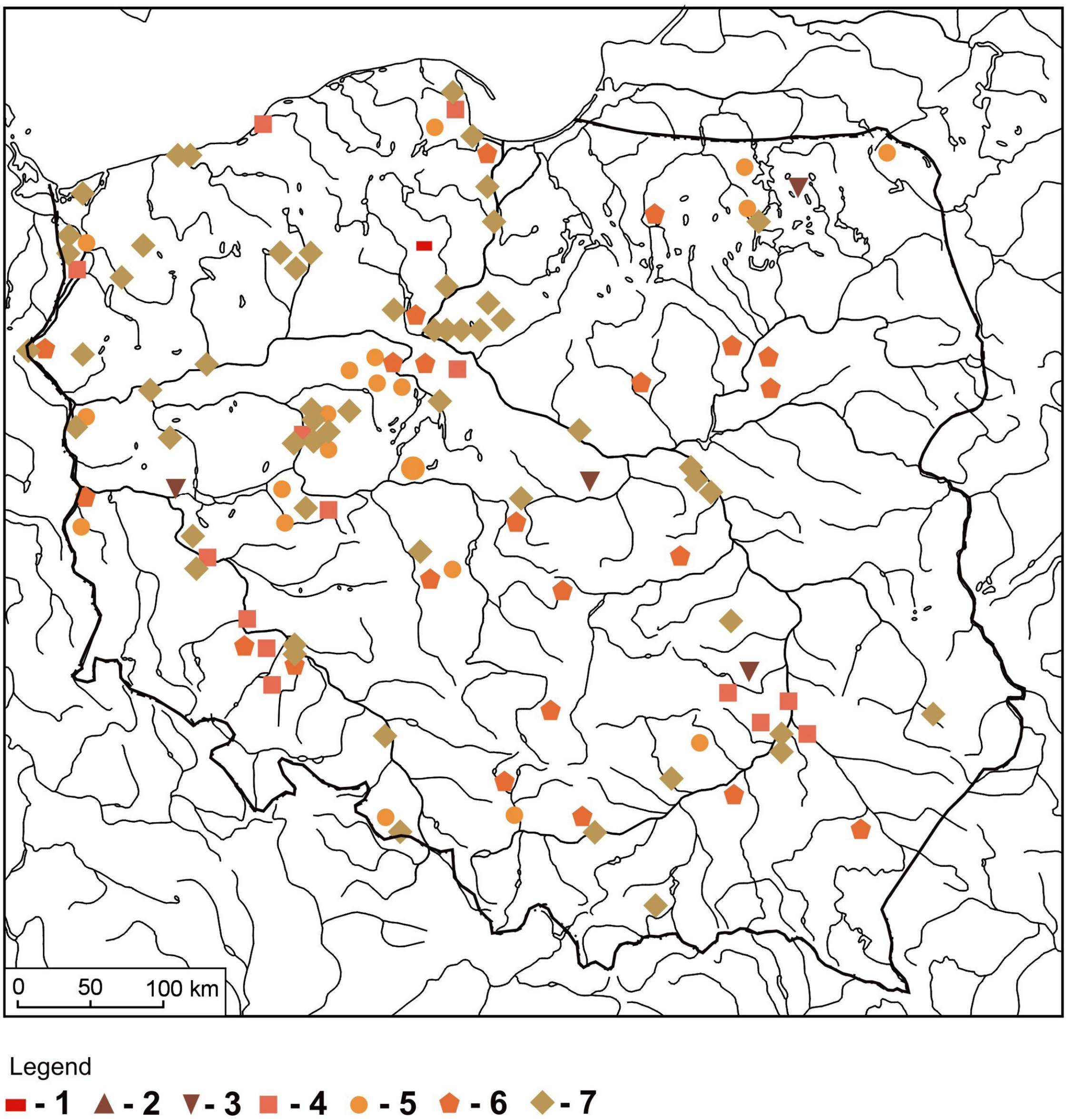

Figure 1. The distribution of archaeological test sites where the bone remains of European beavers were recorded in Poland according to the query carried out by Abłamowicz et al. (2008).
1 – area of study of the relict beaver ponds in the Tuchola Forest, 2 – Palaeolithic, 3 – Mesolithic, 4 – Neolithic, 5 – Bronze Age – early Iron Age (Hallstatt), 6 – La Tene and Roman influence period, 7 – Middle Ages.

cene period, peat cover increasing with time also played a significant role in retention. The increase in peat cover was associated, among other things, with the overgrowth of subsequent generations of beaver ponds (Śnieszko et al., 2020, 2021). The significance of beaver pond sediments as the material building the Holocene bottoms of small river valleys in Poland was systematically neglected in studies on Holocene alluvia despite the earliest suggestions that a considerable share of beaver pond sediments in Holocene alluvia appeared in publications dating back to the first half of the 20th century (Ruedemann and Schoonmaker, 1938; Ives, 1942). Geological documentation of the contribution of Holocene beaver pond sediments in building the floodplain was later presented by a small number of North American and European authors (John and Klein, 2004; Butler and Malanson, 2005; McCullough et al., 2005; De Visscher et al., 2014; Rurek et al., 2016; Levine and Meyer, 2019; Śnieszko et al., 2017, 2020, 2021).

Based on beaver pond sediment surveys, the history of beaver colonisation during the Holocene in Yellowstone Park was recreated (Persico and Meyer, 2009, 2013). Long-term studies of beaver impacts during the Holocene in valleys in the Tuchola Forest have provided material documenting the role of these animals in the Holocene evolution of small river valleys in the Polish Plain (Rurek et al., 2016; Śnieszko et al., 2020, 2021; Rurek 2021). Both beaver ponds and peat cover sustained water retention in the small river valleys throughout the Holocene. The widespread presence of beavers in forest ecosystems during the Holocene fostered flooding and the consequent long-term swamping of valley bottoms (Śnieszko et al., 2020, 2021). With time, and due to increasing anthropopressure, the Holocene beaver population declined. Only 1200 beavers survived in Europe until the 20th century. In 1928, 235 animals of this species (20% of the European population) were present in the basins of the Neman and Pripyat rivers (within the territory of Poland) (Czech 2000).

In the second half of the 20th century, the reintroduction of beavers began in Poland (Sobieralska, 1998; Czech, 2000, 2007; Janiszewski et al., 2009). This has contributed to an increased interest in these animals among researchers and local planning institutions (Stopka, 2011; Szpikowska and Szpikowski, 2012; Giriat et al., 2016; Fajer et al., 2017; Gorczyca et al., 2018; Szpikowski and Szpikowska, 2018). It is estimated that with the contemporary population of *castor fiber* in Poland (between 100,000 and 137,000 individuals), the volume of small-scale water retention in beaver ponds is estimated to be 70 million m^3. However, this retention constitutes only 1.75% of the country's current requirements (Grygoruk, 2008). Thus, at the moment, small-scale retention in beaver ponds is of local significance but is very important for the sustainable development of many regions with protected landscape areas.

In Poland, since the Middle Ages, retention in man-made ponds has partially replaced that in beaver ponds. The oldest form of retention originating from human activities is mill ponds. Watermills were situated in narrow river valleys in necking areas to facilitate the construction of levees. They were often built in valley areas where beaver ponds existed before human impact on the landscape. The increasing number of mills by the 18th century implies that the shrinking retention in ponds built by beavers, associated with the systematically declining size of their population, was partly offset by the retention in mill ponds. However, to date, researchers have not analysed this problem in detail.

Land amelioration was carried out in many parts of the Polish Plain in 1815-1918, 1926-1930, and 1945-1990, which resulted in a severe reduction of water retention in valley bottoms.

At the end of the 20th century, records on the role of beavers in the Holocene evolution of river valleys in Poland are still scarce. From the start of the reintroduction, research has been conducted on its ecology and beaver impact on the modern landscape (Żurowski, 1980; Czech, 2000; Kobojek, 2005, 2013; Janiszewski et al., 2009; Rurek, 2009; Gorczyca et al., 2018; Fajer et al., 2017; Szpikowski and Szpikowska, 2018; Wróbel and Krysztofiak-Kaniewska, 2020; Wróbel, 2020). Surveys have also begun on the role of beavers in the past and their impact on the evolution of the Holocene landscape. Long-term studies of the effects of beaver presence during the Holocene have only been carried out in valleys in the Tuchola Forest area (Rurek et al., 2016; Śnieszko et al., 2020, 2021; Rurek, 2021). Examining fossilised beaver pond sediments has made it possible to assess the role of beavers in Holocene floodplain formation. The sediments of Holocene beaver ponds are an essential component of alluvia in sections of small catchments, which is crucial for reinterpreting the evolution models of these areas during the Holocene.

An attempt to estimate the water retention volume in beaver ponds in the natural environment and to determine the extent to which *anthropogenic small-scale retention in mill ponds has offset the shrinking small-scale retention in beaver ponds* is fundamental for assessing the causes and effects of changes in neo-Holocene ecosystems.

In the context of modern climate change and increasing water scarcity, assessment of the impact of beaver reintroduction in the present times on small-scale retention in specific catchments has also gained importance. We conducted a study in two lowland catchments of the Vistula River basin (i.e. the Brda and Wda catchments) to assess the role of beaver ponds and mill ponds in water retention in the Holocene and the significance of beaver reintroduction in the present times in increasing small-scale water retention in the area.

2. Study area

We studied the natural Holocene and historical anthropogenic small-scale retention in channel ponds within a limited area of the North European Plain (Fig. 2A). For the Brda and Wda catchment areas in the Vistula basin, data were collected documenting contemporary beaver colonisation after restitution of this species, along with archival materials recording the location of watermills since medieval times (some of which were accompanied by mill ponds). Surveys documenting the existence of Holocene ponds before intensified human impact were carried out in small study sites in the Tuchola Forest (catchments of the Brda and Wda rivers, Fig. 2B, 3A and B) where preserved beaver pond sediments were exposed, and in one case, the location of the beaver ponds and mill ponds coincided.

A large section of the Wda and Brda catchment areas is covered by an outwash plain formed by fluvioglacial waters flowing out from the stagnant ice sheet of the Pomeranian phase of the last Pleistocene glaciation (Fig. 4). It extends at an elevation of 120–140 m a.s.l., and the thickness of the fluvioglacial sand and gravel cover varies

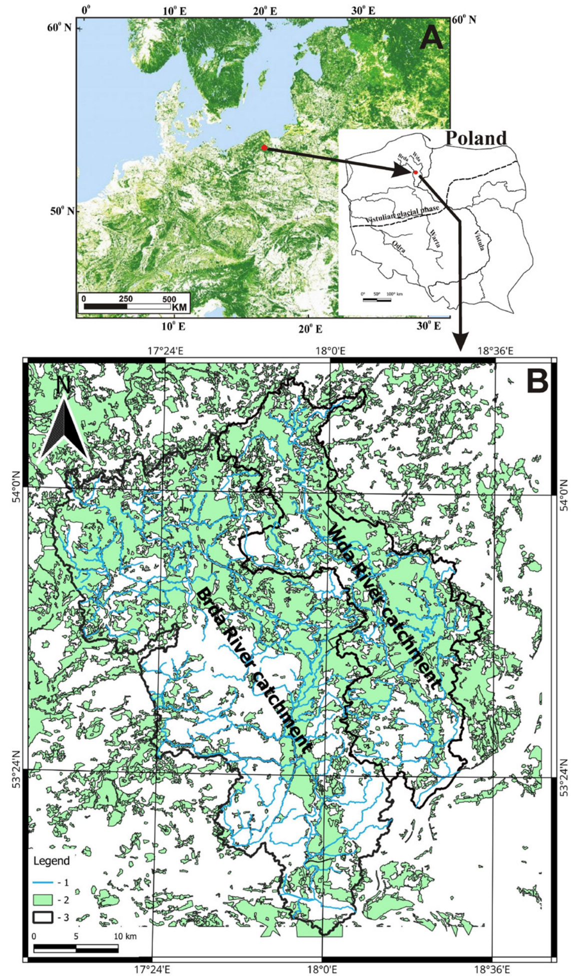

Figure 2. Map location of the study area in Europe (A) and the boundaries of the catchments of the Wda and Brda Rivers (B). Key: 1, water bodies; 2, forest; 3, catchment boundary.

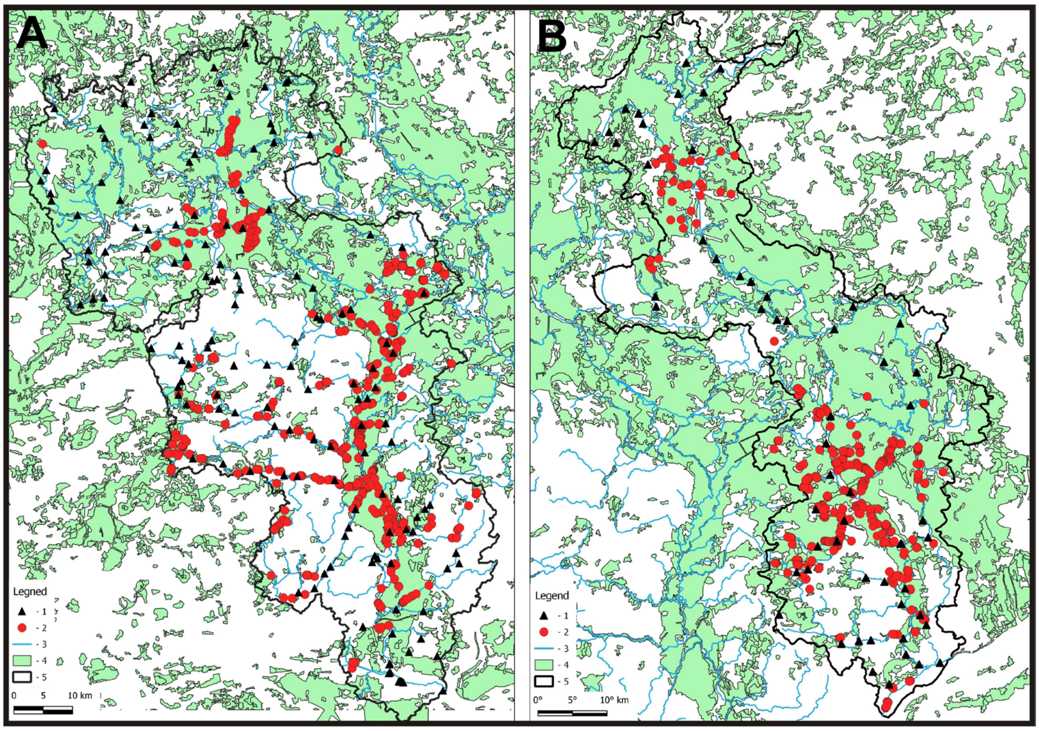

Figure 3. Mill ponds from the Middle Ages to the present day and contemporary traces of beaver colonisation in the Brda (A) and Wda (B) catchment areas. Key: 1: mill ponds; 2: beaver sites; 3: water bodies; 4: forest; 5: catchment boundary.

between 3 m and 60 m (Rurek et al., 2016). Fluvioglacial sand and gravel sediments are adjacent to 'moraine islands' made of glacial till. The absolute altitude of the 'moraine islands' ranges from 140 to 160 m a.s.l. Late Pleistocene and Holocene fluvial processes remodelled the outwash plain surface.

The study area is now located in a temperate climate zone. The precipitation here is variable, ranging from 450 to 600 mm, and the mean air temperature ranges from +2° (in January) to +18.5° (in July). Forests appeared as early as the end of the Pleistocene. The pioneer species among the trees were birch, pine, and alder. During the Holocene, oaks, hornbeams, beeches, and elms appeared. Secondary pine stands are currently predominant in the study area (Filbrandt-Czaja 2006). Deciduous trees were preserved in valley depressions and at loamy heights.

Fauna, typical of the European temperate zone, inhabit forest areas. Since the beginning of

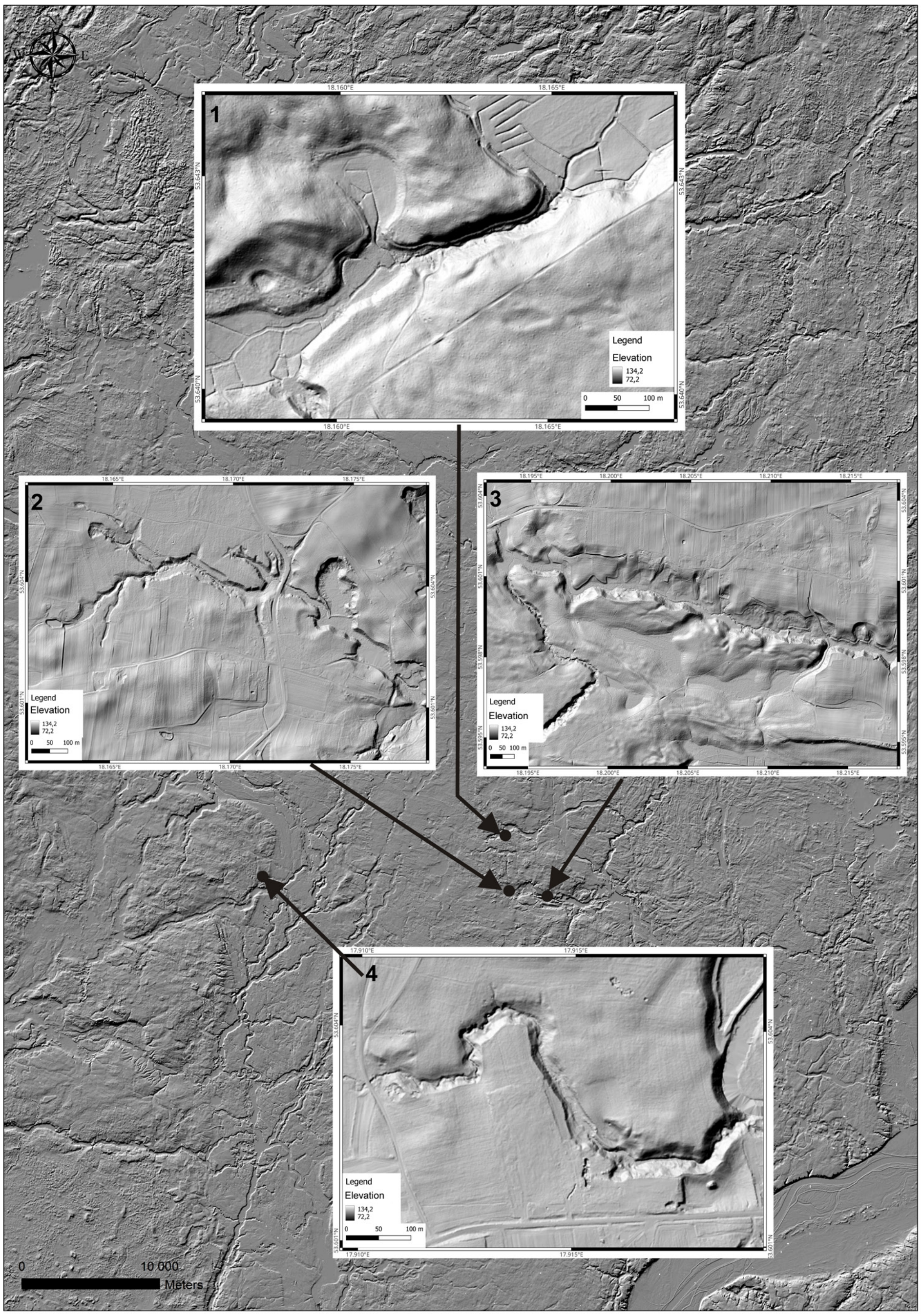

Figure 4. Examples of 1st order valley relief in the Brda and Wda catchment areas (Source: own elaboration based on data from www.geoportal.gov.pl). 1 – the Gołyjonka valley, 2 – the Gajdówka valley, 3 – the Zdrojanka valley, 4 – the Hozjanna valley.

the Holocene, valleys in the study area have been overrun by European beavers (Rurek et al., 2016; Śnieszko et al., 2020). In Poland, conservation measures were implemented for this species as early as the 11th century. Nevertheless, between the 12th and 14th centuries, the beaver population began to decline abruptly. This trend continued throughout Europe, and until the beginning of the 20th century, eight small populations survived on the continent. The area of Tuchola Forest, where the Brda and the Wda catchment study areas are situated, was one of the sites where beavers persisted the longest in Europe. The last traces of Holocene beaver activity date to the early 20th century, and the reintroduction followed as soon as the second half of that century (Śnieszko et al., 2020).

Owing to limited human impact, large sections of natural forest complexes and secondary plantings have been preserved in the study area to the present day. At present, some sections of the studied catchment areas are subject to various forms of landscape protection (e.g. Tuchola Forest National Park, Tuchola Landscape Park, Wda River Landscape Park, Brda Valley Nature Reserve, and Śliwice Protected Landscape Area).

Studies of Holocene beaver pond sediments have been conducted in forested sections of small valleys in the Tuchola Forest, which are currently inhabited by beavers. Two areas were selected for the detailed study. First, sediments from the Holocene and contemporary beaver ponds located away from anthropogenic impacts were studied (Gołyjonka Valley; Fig. 5A, B, C). In the second one, situated at the perimeter of Tuchola town (Hozjanna Valley, Fig. 5D), the analysis covered the sediments of a Holocene beaver pond, mill pond, and contemporary beaver pond.

In the upstream section of the Gołyjonka valley, the river flows through a 200 m long and 10 m wide V-shaped incision. The slopes in this section of the valley have a gradient of 30-25°. Relict beaver pond sediments were preserved in a contemporary cut at the valley bottom (Fig. 5B). This is the only location in the valley where sediments from relict beaver ponds could be explored in the pits. It is also the only site in Poland where Holocene beaver pond sediments have been described (Rurek et al., 2016; Śnieszko et al., 2020, 2021). Only contemporary pond sediments have been described in the rest of the country (Kobojek, 2005, 2013; Stopka,

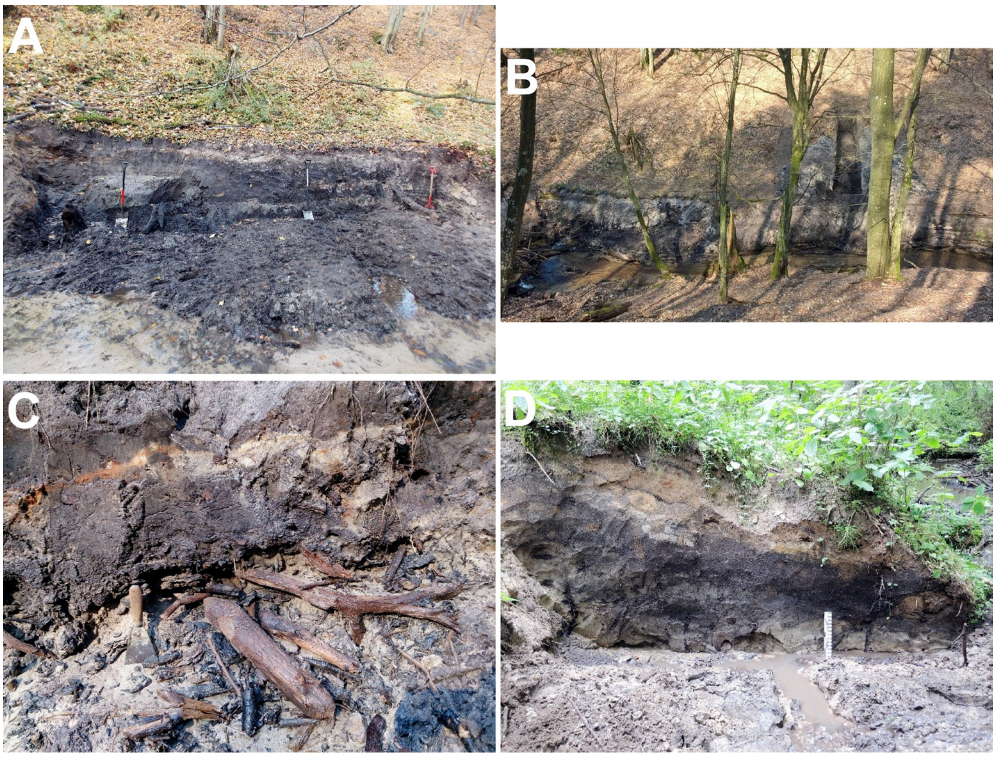

Figure 5. Beaver pond sediments. The Gołyjonka valley A, B - sediments of Holocene beaver ponds at the valley's necking, C - pieces of wood with beaver teeth marks in the beaver pond sediments. D: Bottom sediments from a beaver pond in Hozjanna Valley.

2011; Szpikowska and Szpikowski, 2012; Szpikowski and Szpikowska, 2018).

Beaver pond sediments have been exposed in a section of the Hozjanna River valley (a tributary of the Brda), where a watermill was located in the past. The surveyed valley section is an erosional landform connecting the two landlocked depressions. Relict pond sediments also occurred in the pits (Fig. 5D). The valley features a very narrow and flat bottom (from 5 m to 7 m) and 4-5 m high, steep slopes (from 20° to 30°). The longitudinal profile shows a low slope (5‰), but in the lower 150 m-long-section the slope is 12‰. The valley has been in economic use since the 13th century. A watermill likely operated in the surveyed valley section at that time.

The exact date when the watermill on the Hozjanna River was constructed is unknown, but its operation was documented back to 1346. According to data from the Central Database of Mills in Poland, the location of the Hosianna Mill (reference CeBaDoM/PL/07/WAM-a/00840) is defined by its coordinates: 53°35'24.0"N 17°55'29.0"E (53.590000, 17.924722). Analysis of archival cartographic material and publications by J. Gołaski (2002) showed that the site was also in operation in 1790 (Hosanna Wasser Mühle, *map by Schroetter and Engelhardt,* scale 1: ca. 50,000), 1830 (Hosanna Mühle – *Generalstabskarte*, scale 1:100 000), 1862 and 1863 (Blaskaer Mühle – *Karte von dem Gute Wimislowo*, scale 1:25 000), and 1890 and 1905 (Hosianna Mühle – *Karte des Deutschen Reiches*, 1:25 000). The *Geographical Dictionary of the Kingdom of Poland and other Slavic Countries*, compiled by Sulimierski et al., 1880, p. 161, also testified that the facility was still in operation in the 19th century. The map of 1790 shows no pond next to the Hosianna watermill, indicating that, at that time, the waters of the Hozjanna stream powered the undershot waterwheel. In contrast, the locations of the watermill and the mill pond are documented on two of the 1:25000 scale maps indicated above: *Karte des Deutschen Reiches* and *Karte von dem Gute Wimislowo*. The flow-through mill pond was formed by constructing a levee transverse to the axis of a well-developed river valley at its narrowing point. The watermill was located on the mill pond, approximately 10 m from the base of the levee. The considerable distance between the watermill and the levee was due to the need for a drop, which was necessary to generate power using the overshot wheel. The mill pond basin had an elongated shape, clearly following the course of the stream valley. The pond was 290 m long and had a maximum width of 1.2 m. Based on field surveys and Digital Elevation Model (DEM) measurements, the capacity of the pond was calculated to be approximately 1568 m^3, with a damming height of 1.5 m. Subsequent maps from the 20th century did not display the watermill location or outline of the mill pond (e.g. the International Map of the World (WIG map) of 1931).

The anthroporessure in the study area was limited to agricultural activities. Agricultural crop processing is linked to the miller trade. In the 18th century, there were 165 watermills in the catchments of the Wda and Brda Rivers (both catchments cover 6952 km^2). In the 1930s, 115 mills were located in the area.

We retrieved information on the impact of watermills from the written accounts. For the 16th-18th century period, we used information from conscription registers, town and land registries, and records of inspections and inventories of royal estates. For later periods, we consulted cartographic material: topographic maps at a scale of 1:50,000 drawn between 1796 and 1802, topographic maps at a scale of 1:25,000 from 1872-1874, topographic maps at a scale of 1:25,000 from 1904-1911 and to 1924-1932. Another source of information was *the Geographical Dictionary of the Kingdom and other historical regions of Poland* (1936).

3. Material, methods and results

We collected source material on the problem outlined in the title during field research using paleogeographic methods (Holocene beaver pond sediments) and archival records of the history of mill ponds. The detailed methods for obtaining and visualising the source material are presented in the following subsections.

3.1. Sediments of Holocene beaver ponds

Materials for the study of Holocene beaver pond sediments were acquired from exposed sites preserved in the narrowing areas of small river valleys and cores of intact structures sampled with an Instorf probe in broader valley sections. Ground-penetrating radar (GPR) was also used in broader sections of the eastern part of the Gołyjonka valley. Pieces of wood extracted from beaver pond sediments (some showing beaver teeth marks) and a variety of organic materials from the cores were submitted to the laboratory in Gliwice for dating. Nineteen Holocene beaver pond sediment samples were collected.

Research into the relict traces of beavers in parts of the Tuchola Forest valleys has yielded a wealth of information on the older phases of beaver colonisation during the Holocene. The dating of traces of Holocene beaver colonisation involved the discovery of relict wood-bearing beaver teeth marks in the alluvia of several valleys. Wood extracted from the sediments filling the extensions of these formations using Instorf probes was associated with beaver activity if documented in a secondary deposit. The instorf penetration was limited to a depth of no more than 4.3 m. The deeper parts of the peat bog were penetrated with GPR for technical reasons, and no dating material was obtained from them. Sediments of different Holocene ages may be present in valley neckings, where pond sediments occur in exposed pits at identical depths in different parts of the surveyed valley section. This has been demonstrated in previous studies of the Gołyjonka Valley (Śnieszko et. al., 2020, 2021). To date, no Holocene wood older than 5ka B.P. has been extracted from the beaver ponds. Instead, extensive material documenting the decline in beaver colonisation was obtained. The dating of wood pieces with teeth marks indicates that beavers lived until the early 20th century (Table 1).

The dating was conducted in the Gliwice Radiocarbon Laboratory by the LCS method and one sample was Marek Krąpiec Laboratory in Kraków using the LSC method. Samples were treated with a standard acid-alkali-acid procedure to remove humic acids, chitin, fungal products, carbonates, etc. (Tudyka et al., 2017). Next, the samples were converted

Table 1. The radiocarbon measurements were calibrated using IntCal20 and Post-bomb atmospheric NH-1 calibration curve (Hua et al. 2022; Reimer et al. 2020), sample types, and calibrated data.

Lab. Code	Sample type	Radiocarbon measurement (^{14}C yr BP or pMC)	Calibrated radiocarbon date ranges, probability 68.3% (BC/AD)	Calibrated radiocarbon date ranges, probability 95.4% (BC/AD)
MKL-3319	Piece of wood, Czerska Struga	106.2 ± 0.7%	1956 – 1957 (5.1%) 2004 – 2008 (63.1%)	1956 – 1957 (8.6%) 2003 – 2010 (86.9%)
GdS-3887	Piece of wood, Zdrojanka	99.96 ± 0.49%	1700 – 1725 (18.5%) 1815 – 1835 (18.9%) 1890 – 1910 (19.9%) 1950 – 1955 (10.9%)	1690 – 1730 (24.5%) 1810 – 1920 (59.8%) 1950 – 1955 (11.2%)
GdS-3871	Piece of wood, Zdrojanka	45± 60 (99.27 ± 0.49)	1695 – 1725 (21.5%) 1810 – 1840 (19.5%) 1875 – 1915 (26.3%) 1950 – 1 955 (1.0%)	1685 – 1735 (26.3%) 1805 – 1930 (68.0%) 1950 – 1955 (1.2%)
GdS-3923	A stick from the contemporary dam on the Zdrojanka	102.52 ± 0.65	1955 – 1956 (8.5%) 2013 – 2016 (59.7%)	1955 – 1956 (13.2%) 2012 – 2018 (82.2%)
GdS-4431	silt from the Hozjanna Valley, by the riverbed	0 ± 60 (99.99 ± 0.76)	1695 – 1725 (20.4%) 1810 – 1840 (18.4%) 1845 – 1850 (1.3%) 1865 – 1870 (0.7%) 1875 – 1920 (25.1%) 1950 – 1955 (2.4%)	1680 – 1740 (25.9%) 1750 – 1765 (0.7%) 1800 – 1940 (66.2%) 1950 – 1960 (2.7%)

to C_6H_6 and stored for more than one month to allow all ^{222}Rn isotopes to decay. A more detailed description of the procedures, precision, and accuracy obtained in the GADAM Centre Laboratory in Gliwice was provided by Pawlyta et al. (1998). Liquid scintillation measurements were performed using a Quantulus 1220TM. The ^{14}C dates were calibrated with the post-bomb atmospheric Northern Hemisphere Zone 1 curve (Reimer et al., 2020; Hua et al., 2022) using OxCal v4.4.4 software (Bronk and Ramsey, 2021).

In addition to the search for Holocene beaver pond sediments in valleys that were not altered by human impact, reconnaissance was also conducted in valley sections where mill ponds had operated in the past.

At the former watermill site in the Hozjanna Valley, pits were made near the riverbed during fieldwork in 2021 to gain insight into the sediment sequence. Mineral and organic sediments were found to fill two shallow overgrown bodies of still water. Samples taken from these for C14 dating were examined at the Gliwice Radiocarbon Laboratory at the Silesian University of Technology (Table 2). Dating of the organic matter from the fill of the ponds implies that the older beaver pond existed even before the appearance of the oldest mill pond and the younger beaver pond after the decommissioning of the youngest mill pond. The presence of these water bodies in the channel zone could be related only to the existence of beaver dams.

Table 2. The results of the dating of organic matter from relict beaver pond fills were located within the boundaries of a former mill pond in Hozjanna Valley.

Lab. No.	Sample type	Carbon-14 dating {C14 concentration}	Calendar dating (calibrated) - intervals 68.2% (cal. AD/BC)	Calendar dating (calibrated) - intervals 95.4% (cal. AD/BC)
GdS-4431	silt from a beaver pond, depth of 40 cm	0 ± 60 BP (99.99 ± 0.76 pMC)	1690 – 1730 AD (20.4%) 1810 – 1850 AD (19.7%) 1860 – 1920 AD (25.8%) 1950 – 1960 AD (2.4%)	1680 – 1740 AD (25.9%) 1750 – 1770 AD (0.7%) 1800 – 1940 AD (66.2%) 1950 – 1960 AD (2.7%)
GdS-4432	silt from a beaver pond, depth of 50 cm	725 ± 65 BP	1225 – 1305 AD (57.5%) 1365 – 1385 AD (10.8%)	1175 – 1905 AD (1.3%) 1205 – 1400 AD (94.2%)

3.2. Changes in the number and location of watermills in the catchments of the Brda and the Wda

The earliest records of watermills operating in the study area date back to the 13th century and concern the Grabowo Watermill on a tributary of the Vistula (1239) and the Raciąski Watermill on the Struga Raciąska (1277). In the second half of the 14th century, the number of active watermills rose to 29 during the decline of the miller's trade dissemination stage (Fig. 6A), and remained similar in the 15th century (30 facilities) (Fig. 6B). However, it is worth noting that at least 59 of the 215 sites confirmed during the survey (27.4 %) were used as water mills by the end of the Middle Ages.

By the 16th century, the number of active mills had increased to 89, leading to significant changes in the spatial distribution of watermills in the study area. Many (i.e. 28) operated on sites already in use, whereas the remaining 61 watermills were located on new sites. Concurrently, this means that more than half of the sites from the medieval period lost their economic importance (31 sites). The indicated changes stemmed from the development of the miller's trade due to technical advances and an increase in demand, primarily for products derived from the milling of cereal grains (flour and groats). At that time the increased number of watermills was, to a lesser extent, associated with the development of so-called secondary milling production in sawmills, hammer mills, fulling mills, and paper mills. Production usually develops in the existing locations of the former grain mill, which has fostered the construction of multiwheel water

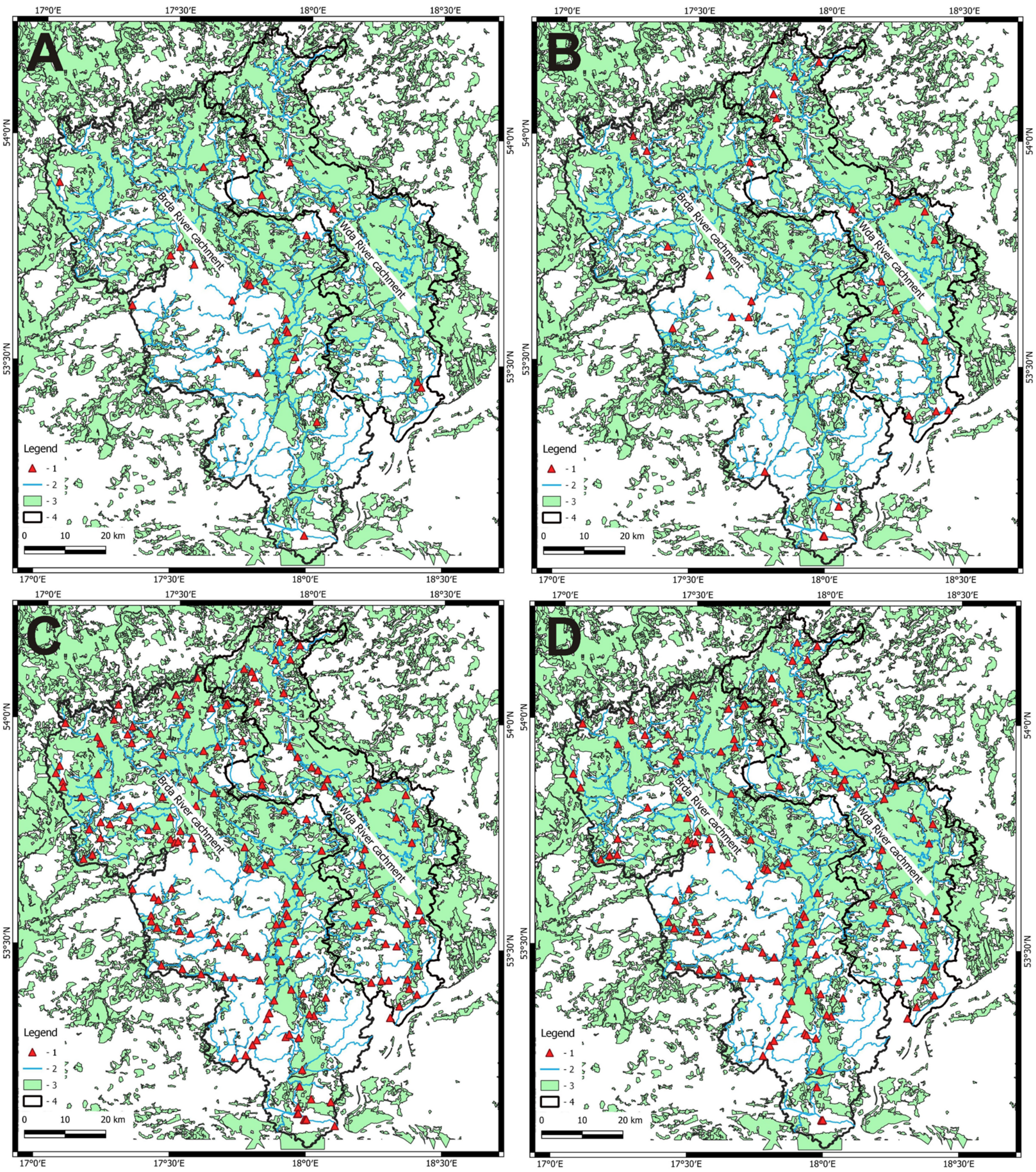

Figure 6. Locations of mill ponds in the catchments of Brda and Wda in the 14th (6A), 15th (6B), 19th (6C), and 20th (6D) centuries. Key: 1 – watermills, 2 – water bodies, 3 – forests, 4 – boundary of the catchments of Brda and Wda.

mills. Undershot wheels are usually arranged in a row along the river, whereas overshot wheels are arranged in parallel, sometimes on opposite banks (Baranowski, 1977). In the 16th century, the number of watermills with overshot wheels increased rapidly (Samsonowicz, 1954; Podgórski, 2004). The main reasons were economic factors, which caused the loss of profits, and the economic significance of inefficient watermills with undershot wheels. Overshot wheels are typically used in new locations. However, because of the difficulty in ensuring large water drops, overshot waterwheels are usually smaller than undershot waterwheels, that is, their diameters ranged from 1.7 m to 2.2 m. The watermill location had to be selected more carefully and involved the construction of levees and the storage of water in the mill ponds. For many flow-through mill ponds, pond basins are natural, with broader sections of the valleys of small watercourses. The site adaptation consisted of a levee laid transverse to the axis of the valley below the broader sections. Beavers previously used the indicated locations for dams on more than one occasion, with the water level resulting from the animals' activity usually being lower than that due to human activity sufficient to install an overshot waterwheel. Swedish wars in the 17th century considerably accelerated the displacement of the undershot waterwheels. After their completion, many watermills with undershot wheels were not reconstructed. On the other hand, if the physiographic features were allowed using overshot wheels, they were introduced relatively quickly. By the 18th century, these were the most common type in Poland (Baranowski, 1977).

At the end of the 18th century, 165 watermills operated in the study area, indicating that the highest number of sites (76.7 %) were in use at any one time. At that time, the water regime in the study area was nearly natural. Favourable drainage conditions meant that 70 of the 165 active watermills were located on new sites, distinguished by the natural predispositions of the land. They were located in narrow river valleys in necking areas, which facilitated the construction of levees and storage of water in flow-through ponds.

During the first half of the 19th century (Fig. 6C), the number of watermills declined to about 150, undoubtedly due to war damage. However, the failure to reconstruct watermills after the Peace of Vienna also implied the depletion of water resources (Gołaski, 2002). Decommissioning mainly concerned mills on small watercourses, which were probably only periodically active; therefore, this process had no significant impact on water retention rates. The number of watermills declined again in the second half of the 19th century owing to a scarcity of water resources, with an increase in the requirements regarding the demand for water and drop size. Only efficiently performing facilities could compete with the increasingly commissioned steam mills. In addition, far-reaching modifications of the water regime were made in the study area in the 19th century, which led to the deterioration of runoff and a reduction in water resources in the catchments. From the late 19th century, the power of falling water was replaced by the power generated by internal combustion engines or electric motors in many mill facilities. In some watermills, the energy source has remained a conventional waterwheel or is possibly replaced by a water turbine (Francis or Kaplan). The indicated changes in economic conditions signified a gradual decrease in the number of active watermills. At the end of the 19th century, there were 141 active mills, whereas in the 1930s, there were only 115 (Fig. 6D). The number of mills decreased by 18.5% at that time. Watermill decommissioning intensified after World War II. Privately owned watermills were obstacles to the new totalitarian social and economic regime. Less efficient mills were closed. In the 1960s, 69 mills were still in operation, but only some of them used water as a power source.

The spatial diversification of environmental features determines the distribution of watermills in the study area. Indeed, the number of watermills was driven by water resources and landform gradients on the one hand and the economic need for energy on the other. This relationship is explicit in the Polish Plain (Gołaski, 2002; Podgórski, 2004). In addition, distinct options for using the respective sites and anthropogenic impacts made watermills economically significant at different times. The durations of their functions are also very different. Thus, the order in which the watermills were built only partially reflects the physiographic attractiveness of the surveyed sites. The analysis showed that the distributions were uneven. The concentration of watermills in particular watersheds was highest in the Krajeńskie Lake District in the Brda catchment and on the Wda and its tributaries. Between 1790 and 1960, there were 141 active watermills in the Krajeńskie Lake District, which makes 11.1 mills per 100 km^2. For the Tuchola Forest, the indicator was 9.0 watermills per 100 km^2, and for the catchment area of the Lower Brda tributaries, it was 7.8 watermills/100 km^2. The smaller number of watermills in the Tuchola Forest stems from the low population density, dense forest cover, and inability to build watermills on Brda as the river was used for floating timber (Gołaski, 2002). The Brda River has the highest energy resources. However, the direct use of the river was mainly within the bigger cities of Bydgoszcz and Koronowo, which does not need to be discussed in detail because of the topic at hand.

3.3. Attempt to estimate the water retention in beaver ponds and mill ponds

Estimates of water resources stored in selected catchments in beaver ponds and mill ponds were based on the implications of publications on beaver activity in lowland ecosystems and the estimated amount of water stored in modern flow-through ponds in the study area.

3.3.1. Source material for spatial analyses

The latest data on the distribution of beavers in the study area were made available by the Regional Directorate for Environmental Protection in Bydgoszcz (RDOŚB) and the Regional Directorate for Environmental Protection in Gdańsk (RDOŚG). Data provided by the RDOŚB refer to the period from 2013 to 2015 and data from the RDOŚG to the years 2017-2018. We acquired information on the locations of the beaver dams, feeding grounds, and burrows. In the Brda catchment, 77 ponds were found, and in the Wda catchment, there were 111 ponds.

For the spatial analyses, the "Vector thematic layers of updated water management plans (aPGW)" were used, downloaded from the server at www.dane.gov.pl. Only vector layers related to surface water (flowing and still water) and the boundaries of the Brda and Wda catchments were selected from the hydrology data package. In addition, we used the data for selecting watercourses that formed the basis for calculating the estimated water volume in the analysed catchments.

Spatial analyses of vector data were performed using QGIS software ver. 3.26. Using this software, source material was selected and various visualisations were produced, as described in the following paragraphs.

We used predesigned vector layers to determine the estimated water retention in beaver ponds during the Holocene. To calculate the maximum potential retention in the beaver ponds, we selected watercourses with channel widths of up to 5 m, assuming that these were channels where beavers commonly built dams. On wider watercourses, such levees are only occasionally found (Żurowski, 1992; Butler and Malanson, 2005). In this way, we established the maximum potential length of watercourses inhabited by beavers before human impact. For the Wda catchment, it was 407 km (57% of all watercourses in the catchment), and for the Brda catchment, it was 1136 km (75% of all watercourses in the catchment) (Table 3).

To estimate water retention in mill ponds in the Brda and Wda catchment areas, we retrieved data from historical sources, as well as from archival and contemporary cartographic material, which allowed us to establish mill pond locations since the Middle Ages and data on average water retention in the mill ponds (Podgórski, 2004). According to Podgórski (2004), for 34 mill ponds in Chełmno Lake District (with an average damming level between 1872 and 1874), the mean pond area was 1.68 ha. Furthermore, a comparative study was carried out in Hozjanna Valley on the amount of contemporary retention in beaver ponds and a mill pond that was active until the early 20th century.

3.3.1.1. Estimated water retention in beaver ponds

To estimate water retention in beaver ponds prior to human impact on the landscape

- we calculated the length of the selected watercourses in the Brda and Wda catchments on which beavers could have built dams – after Horton's (1945) watercourse width was assumed to be up to 5 m, Strahler stream orders 1, 2, and 3.
- we determined the maximum number of beaver dams found at a single time under natural conditions following Żurowski (1992);
- we calculated the mean water retention in a beaver pond using data from 25 ponds in the Tuchola Forest valleys following Rurek et al. (2016).

Table 3. Water retention in beaver ponds in the natural landscape (1st, 2nd, 3rd order valleys)

Catchment area	Length of watercourses for potential settlement by beavers [in km]	Number of beaver families	Number of beavers	Maximum beaver pond count	Maximum estimated water retention volume in the ponds [in million m^3]
The Brda	1136	1704	6305	8520	9 269 760
The Wda	407	610	2259	3053	3 321 664
Total	1543	2314	8564	11573	12 591 424

3.3.1.2. Estimated retention in mills ponds

Considering the variations in the surface area of mill ponds in the study area at the turn of the 20th century, we adjusted the average mill pond surface area. The average adjusted pond area (for 52 ponds) was 17826 m^2. Assuming an average pond depth of 1.2 m, the average pond capacity was 21391 m^3. Given the above values, we estimated the maximum water retention volume for the studied ponds from the Brda and the Wda catchments in the 2nd half of the 18th century to be over 3 million m^3, and later it systematically decreased to approximately. 2.2 million m^3 in the 1st half of the 20th century (Table 4).

Table 4. Retention in mill ponds (1st, 2nd, 3rd order valleys)

Catchment area	Number of objects with mill ponds				Maximum estimated volume of water retention in the ponds [m^3]			
	2nd half of 18th cen.	1st half of 19th cen.	2nd half of 19th cen.	1st half of 20th cen.	2nd half of 18th cen.	1st half of 19th cen.	2nd half of 19th cen.	1st half of 20th cen.
The Brda River	108	99	95	76	2 310 228	2 117 709	2 032 145	1 625 716
The Wda River	34	32	30	27	727 294	684 512	641 730	577 557
Total	142	131	125	103	3 037 522	2 802 221	2 673 875	2 203 273

The estimated results indicate that, in the study area, the maximum water retention in beaver ponds in the natural environment could be up to four times the maximum water retention in mill ponds. When assessing the magnitude of disparities, it should be noted that, until land amelioration commenced in that area, indirect beaver activity-related water retention existed in peat bogs formed in overgrown beaver ponds.

3.3.1.3. Local retention in mill ponds and beaver ponds

In Hozjanna Valley, we retrieved data for a short river section where a historic mill pond was located and where beavers have now settled. Based on sediment dating of the relict beaver pond, we determined that beaver dams existed in this area before the mill's construction. The mill pond was 280 m long, with a maximum width of 14 m (7 m was assumed as the average). The mean depth was 0.8 m. Calculations of the water volume in the mill pond imply that it could contain approximately 1568 m^3 of water when used.

Currently, there are eight small channel ponds in the Hozjanna Valley at the landform necking (eight ponds per 1 km of watercourse), which store approximately 434 m^3 of water, which is almost four times less than the estimated retention in the mill pond. Currently, water retention in beaver ponds in other parts of the Brda and Wda catchments is insignificant. Where we have data on the current location of beaver ponds in individual valleys, water retention in beaver ponds is even lower than that in the Hozjanna Valley.

Based on spatial data, we established that the number of beaver ponds in both catchments varied along a specific stream length inhabited by beavers. For the rivers of the Brda catchment – in the Krówka River valley it is 1.4 ponds per 10 km, in the Kicz River valley 3 ponds per 10 km, and in the Struga Graniczna valley 2.6 ponds per 10 km. For the rivers of the Wda catchment – in the Ryszka River valley it is 3.3 ponds per 10 km, in the Sobina River valley 3.6 ponds per 10 km, and in the Prusina River valley 1.4 ponds per 10 km.

4. Conclusions

Managing water resources in the catchment area in the face of growing water scarcity due to the increasing aridity of the climate is a key problem in planning the sustainable development of regions. In the past, small-scale water retention in beaver ponds and man-made ponds played an essential role in the water balance of the natural and agricultural landscapes on the Polish

Plain. Sufficient documentation of the effects of beaver presence in the contemporary and pre-anthropogenic landscapes testifies to the significant role of these animals in shaping the terrain relief and water regime in the Holocene. The growing water deficit prompted us to examine the role of small-scale water retention in contemporary beaver ponds in the context of their role in the Holocene landscape.

The main man-made water retention facilities in the designated study area are mill ponds. Their numbers increased until the 18th and 19th centuries when beaver ponds almost completely disappeared in Europe. In a short time, in the examined section of the Polish Plain, decreasing beaver pond retention and expanding mill pond retention co-existed. Afterwards, a reverse process took place from the mid-20th century, when the beaver population began to rebuild and the local miller's trade declined.

After estimating the proportions of natural Holocene beaver pond retention, mill pond retention, and contemporary retention after beaver restitution in the study area, we established the following:

– the estimated maximum water retention in the beaver ponds in the Brda and Wda catchments under natural conditions was almost four times higher than that in the mill ponds at the peak of their development. This difference should be increased by peat bog retention (i.e. the amount of retention that is difficult to estimate is indirectly related to the Holocene overgrowing beaver ponds where peat accumulated).
– based on calculations of the volume of water stored in a section of the Hozjanna Valley, it was shown that water retention in the now non-existent mill pond was greater than the beaver pond retention in the same part of the valley before the watermill appeared and greater than water retention in contemporary beaver ponds. This estimate for a specific section of the river channel may create a false impression of the significant role of water retention in mill ponds.

Long-term beaver ponds and man-made mill pond retention in the catchment areas were efficiently reduced by land amelioration practices. Contemporary water retention in beaver ponds after the restitution of beavers in the second half of the 20th century cannot match natural retention in the period preceding human economic activity and retention in mill ponds. This will probably not offset the adverse effects of valley floor drainage resulting from future land irrigation practices. One of the reasons is the lack of understanding, even among 'promoters' of sustainable development, of the positive role of beavers in shaping the water regime in river catchments and consent to limit the population growth of this species.

References

Abłamowicz D., Rurek M., Śnieszko Z. 2008. Znaczenie badań skutków obecności bobrów w pradziejach dla lokalnych i regionalnych rekonstrukcji paleogeograficznych, (red.) D. Makowiecki, R. Abłamowicz, D. Abłamowicz, K. Smiarowski i M. Makohonienko, wydanie konferencyjne. 3rd Symposium of Environmental Archaeology, Archaeozoological research in Poland and Middle – East Europe, Data – Methods – Interpretations, Koszęcin, 35-36 [In Polish with English abstract]

Baranowski B. 1977. Polskie młynarstwo. Zakład Narodowy Imienia Ossolińskich, Wrocław-Warszawa-Kraków-Gdański, 143 [In Polish].

Bronk Ramsey C. 2021. OxCal 4.4. Available at: http://c14.arch.ox.ac.uk/oxcal.

Butler D. R., Malanson G. P. 2005. The geomorphic influences of beaver dams and failures of beaver dams. Geomorphology 71, 48-60.

Czech A. 2000. Bóbr. Wydawnictwo Lubuski Klub Przyrodników, Górzyca, Polska, 99 [In Polish].

Czech A. 2007. Krajowy plan ochrony gatunku – Bóbr europejski (*Castor fiber*), Kraków, 46 [In Polish].

De Visscher M., Nyssen J., Pontzeele J.,Billi P., Frankl A. 2014. Spatio-temporal sedimentation patterns in beaver ponds along the Chevral river, Ardennes, Belgium, Hydrological Processes 28, 1602-1615.

Fajer M., Malik I., Waga J.M., Wistuba M., Woskowicz-Ślęzak B. 2017. Contemporary adaptation of anthropogenically-transformed river valleys by European beavers Castor fiber (examples from Poland's Opole Plain and Woźniki-Wieluń Upland). Polish Geographical Review 89(3), 467-489 [In Polish with English abstract].

Filbrandt-Czaja A. 2006. Studia nad historią szaty roślinnej i krajobrazu Borów Tucholskich. Wydawnictwo Naukowe UMK, Toruń, 131 [In Polish with English abstract].

Giriat D., Gorczyca E., Sobucki M. 2016. Beaver ponds' impact on fluvial processes (Beskid Niski Mts., SE Poland), Science of The Total Environment 544, 339-353.

Gołaski J. 2002. Atlas rozmieszczenia młynów wodnych w dorzeczach Warty, Brdy i części Baryczy w okresie 1790-1960, część 4: Brda i Górna Noteć. Akademia Rolnicza, Poznań. Strona 40 – Arkusz 5 [In Polish].

Gorczyca E., Krzemień K., Sobucki M., Jarzyna K. 2018. Can beaver impact promote river renaturalization? The example of the Raba River, southern Poland. Science of The Total Environment 615, 1048-1060.

Grygoruk M. 2008. Metodyka szacowania objętości retencyjnej stawów bobrowych oraz ich oddziaływania na stosunki wodne zlewni leśnych. Studia i Materiały Centrum Edukacji Przyrodniczo-Leśnej 10 2(18), 162-172 [In Polish].

Grygoruk M., Nowak M. 2014. Spatial and Temporal Variability of Channel Retention in a Lowland Temperate Forest Stream Settled by European Beaver (*Castor fiber*). *Forests 5(9),* 2276-2288.

Horton R.E.. 1945. Erosional Development Of Streams And Their Drainage Basins; Hydrophysical Approach To Quantitative Morphology. Geological Society of America Bulletin 370(28), 2011.

Hua Q., Turnbull, J., Santos, G., Rakowski, A., Ancapichún, S., De Pol-Holz, R., Hammer S., Lehman S.J., Levin I., Miller J.B., Palmer J.G., Turney, C. 2022. Atmospheric radiocarbon for the period 1950-2019. Radiocarbon 64(4), 723-745, DOI:10.1017/RDC.2021.95.

Instytut Meteorologii i Gospodarki Wodnej. 2022. Dane pomiarowo obserwacyjne IMGW, https://danepubliczne.imgw.pl [In Polish].

Ives R.L. 1942. The beaver–meadow complex. Journal of Geomorphology 5, 191-203.

Janiszewski P., Gugołek A., Nowacka D. 2009. Characteristics of the European Beaver (Castor fiber) Population in the Tuchola Forest. Zeszyty Naukowe Polskiego Towarzystwa Zootechnicznego V(1), 106-111 [In Polish with English abstract].

John S., Klein A. 2004. Quaternaire Hydrogeomorphic effects of beaver dams on floodplain morphology: avulsion processes and sediment fluxes in upland valley floors (Spessart, Germany). Quaternaire V(15), Numéro 1, Année, 219-231.

Kobojek E. 2005. Środowiskowe skutki reintrodukcji bobra (Castor fiber) w dolinie Rawki. Przegląd Geograficzny 77(3), 383–396 [In Polish with English abstract].

Kobojek E. 2013. Wpływ działalności bobrów na lokalne procesy fluwialne w wybranych rzekach równiny łowicko-błońskiej. Acta Universitatis Lodziensis Folia Geographica Physica 12, 17-22, [In Polish with English abstract].

Levine R., Meyer G.A. 2019. Beaver-generated disturbance extends beyond active dam sites to enhance stream morphodynamics and riparian plant recruitment. Scientific Reports 9/8124, doi.org/10.1038/s41598-019-44381-2.

McCullough J.L., Harper, J.L., Eisenhauer D.E., Dosskey M.G. 2005. Channel aggradation by beaver dams on a small agricultural stream in eastern Nebraska. Journal of the American Society of Agricultural and Biological Engineers 57, 107-118.

Pawlyta, J., Pazdur, A., Rakowski, A., Miller, B.F., Harkness, D.D. 1998. Commissioning of Quantulus 1220TM liquid scintillation beta spectrometer for measuring ^{14}C and ^{3}H at natural abundance levels. Radiocarbon 40(1), 201–209.

Persico L., Meyer G. 2009. Holocene beaver damming, fluvial geomorphology, and climate in Yellowstone National Park, Wyoming, Quaternary Research, DOI:10.1016/j.yqres.2008.09.007, 2-14.

Persico L., Meyer G. 2013. Natural and historical variability in fluvial processes Beaver activity, and climate in the Greater Yellowstone Ecosystem. Earth Surface Processes and Landforms 38, 726-750.

Podgórski Z., 2004. The influence of the construction and functioning of watermills on the relief of the land and surface water of the Chełmno Lakeland and the adjoining parts of the Vistula and Drwęca valleys. Wydawnictwo Uniwersytetu Mikołaja Kopernika, 203, [In Polish with English abstract].

Reimer P.J., Austin WEN, Bard E, Bayliss A, Blackwell PG, Bronk Ramsey C, Butzin M, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kromer B, Manning SW, Muscheler R, Palmer JG, Pearson C, van der Plicht J, Reimer RW, Richards DA, Scott EM, Southon JR, Turney CSM, Wacker L, Adolphi F, Büntgen U, Capano M, Fahrni SM, Fogtmann-Schulz A, Friedrich R, Köhler P, Kudsk S, Miyake F, Olsen J, Reinig F, Sakamoto M, Sookdeo A, Talamo S. 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62(4), 725-757.

Ruedemann R., Schoonmaker W.J. 1938. Beaver-dams as geologic agents. Science 88, 523-525.

Rurek M. 2009. Lokalne zmiany środowiska przyrodniczego wywołane działalnością bobra europejskiego (*Castor Fiber* L.) w okolicy Trzebcin (powiat tucholski). Promotio Geographica Bydgostiensia IV, 119-127 [In Polish with English abstract].

Rurek M., Śnieszko Z., Makohonienko M. 2016. Contemporary and fossil Beaver ponds In small River Valleys on the area of Bory Tucholskie (Nord European Plain). Kazimierz Wielki University Press, Poland, 136, [In Polish with English summary].

Rurek M. 2021. Characteristics of Beaver Ponds and Landforms Induced by Beaver Activity, S Part of the Tuchola Pinewoods, Poland. Water 13(24), article number 3641, DOI: https://doi.org/10.3390/w13243641.

Samsonowicz H. 1954. Rzemiosło wiejskie w Polsce XIV-XVI w. Towarzystwo Miłośników Historii. Państwowe Wydawnictwo Naukowe, Warszawa, [In Polish].

Słownik Geograficzny Państwa Polskiego i ziem historycznie z Polską związanych (1936), Pomorze Polskie. Pomorze Zachodnie. Prusy Wschodnie T.1, Z.7, [In Polish].

Sobieralska R. 1998. Ssaki. [In:] Przyroda Ziemi Świeckiej, (Ed.) J. Pająkowski. Towarzystwo Przyjaciół Dolnej Wisły, Świecie, 174, [In Polish]

Stopka R. 2011. Geomorfologiczne skutki działalności bobra europejskiego Castor fiber w dolinie górnego Sanu. Roczniki Bieszczadzkie 19, 319-334, [In Polish].

Szpikowska G., Szpikowski J. 2012. Właściwości fizykochemiczne wód rozlewisk bobrowych w dolinie Kłudy (górna Parsęta). Monitoring Środowiska Przyrodniczego 13, 95-102, [In Polish].

Szpikowski J., Szpikowska G.. 2018. Akumulacja osadów w rozlewiskach bobrowych w świetle oceny wielkości denudacji mechanicznej zlewni młodoglacjalnej (Kłuda, Pomorze Zachodnie). [In:] Geneza, Litologia i Stratygrafia Utworów Czwartorzędowych, Tom VII. (Eds.). A. Kostrzewski, A. Stach, M. Majewski, Wydawnictwo UAM w Poznaniu, 197-204, [In Polish].

Sulimierski F., Walewski W., Krzywicki J., Chlebowski B. (Eds.). 1880. Słownik geograficzny Królestwa Polskiego i innych krajów słowiańskich. Vol. 3. Warszawa, 161.

Śnieszko Z., Rurek M., Rzetała M. 2017. Significance of relief-forming activities by castor fiber L. for the evolution of Holocene floodplains of small river valleys (results of studies conducted in Poland). [In:] 17th International Multidisciplinary Scientific GeoConference (SGEM 2017): Conference proceedings, Albena, Bulgaria, 29 June – 5 July 2017, Vol. 17 Science and Technologies in Geology, Exploration and Mining, iss. 11. Geology. Mineral processing / ed. Jean Pierre Burg, Sofia, STEF92 Technology LTD: 523-529 [DOI: 10.5593/sgem2017/11].

Śnieszko Z., Rurek M, Hojan M. 2020. The role of beavers in the Holocene landscape evolution of the small river valleys (the Tuchola Forest – North European Plain). Kazimierz Wielki University Press, Bydgoszcz, Poland, 109.

Śnieszko, Z.; Rurek, M.; Hojan, M. 2021 Medieval Relict Beaver Ponds in the Polish Plain: Studies from the Tuchola Forest. Water 13, 777. DOI: doi.org/10.3390/ w13060777.

Tudyka K., Pazdur A., De Vleeschouwer F., Lityńska-Zając M., Chróst L., Fagel N. 2017. Holocene elemental, lead isotope and charcoal record from peat in southern Poland. Mires and Peat 19, Article 07, 1–18, DOI: 10.19189/MaP.2016.OMB.257.

Wróbel, M. 2020. Population of eurasian beaver (*Castor fiber*) in Europe. Global Ecology and Conservation 23, e01046 https://doi.org/10.1016/j.gecco.2020.e01046.

Wróbel M., Krysztofiak-Kaniewska A. 2020. Long-term dynamics of and potential management strategies for the beaver (*Castor fiber*) population in Poland. European Zoological Journal 87(1), 116-121.

Żurowski, W. 1980. Bóbr europejski w Polsce. Przegląd Hodowlany 48(11), 18-24, [In Polish].

Żurowski, W. 1992. Building Activity of Beavers. Acta Theriologica 37, 403-411.