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Article

Spatial and Temporal Variability of Channel Retention in a Lowland Temperate Forest Stream Settled by European Beaver (*Castor fiber*)

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Abstract: Beaver ponds remain a challenge for forest management in those countries where expansion of beaver *(Castor fiber)* is observed. Despite undoubted economic losses generated in forests by beaver, their influence on hydrology of forest streams especially in terms of increasing channel retention (amount of water stored in the river channel), is considered a positive aspect of their activity. In our study, we compared water storage capacities of a lowland forest stream settled by beaver in order to unravel the possible temporal variability of beaver's influence on channel retention. We compared distribution, total damming height, volumes and areas of beaver ponds in the valley of Krzemianka (Northeast Poland) in the years 2006 (when a high construction activity of beaver was observed) and in 2013 (when the activity of beaver decreased significantly). The study revealed a significant decrease of channel retention of beaver ponds from over 15,000 m^3 in 2006 to 7000 m^3 in 2013. The total damming height of the cascade of beaver ponds decreased from 6.6 to 5.6 m. Abandoned beaver ponds that transferred into wetlands, where lost channel retention was replaced by soil and groundwater retention, were more constant over time and less vulnerable to the external disturbance means of water storage than channel retention. We concluded that abandoned beaver ponds played an active role in increasing channel retention of the river analyzed for approximately 5 years. We also concluded that if the construction activity of beaver was used as a tool (ecosystem service) in increasing channel retention of the river valley, the permanent presence of beaver in the riparian zone of forest streams should have been assured.

Keywords: beaver; hydrology; river; retention; water storage; forest; Krzemianka

1. Introduction

The role of beaver (*Castor* sp.) in shaping landscapes, ecological feedbacks and hydrological conditions of riparian forests challenges the management of these ecosystems [1–11]. Among the ecosystem alterations induced by construction activity of beaver, increased water storage capacity and related changes in flow regime and sedimentation–erosion balance remain of the highest importance for both catchment-scale water management and local-scale maintenance of forest environment [12–20]. The increasing abundance of European beaver (*Castor fiber*) populations in Central and Eastern Europe, reported in the late 20th and in the beginning of the 21st century, entailed colonization of new habitats by these rodents, which along with the intensification of agriculture and forestry, remained a cause of conflict at the interface of land use and environmental conservation [21,22]. These conflicts either have an origin in foraging behavior of beaver (cutting trees, destroying crops) or in their construction activity (building dams, digging burrows). Despite that, beaver ponds—small reservoirs that appear as a result of damming streams, canals or ditches—might also be considered an added value to water storage in a local and regional scale, as they significantly increase the channel retention (water storage capacity of river channel) of rivers settled by these rodents [12,19,23,24]. Moreover, the scale of hydromorphological changes induced by beaver was also seen as a valuable enhancement of river restoration in forested landscapes [25].

Although the volumes of beaver ponds are easily assessed in terms of their quantitative relevance to local hydrology [9,15,23], the temporal stability of beaver ponds as water storage reservoirs are so far considered in the literature mostly in dynamic mountainous environments and in reference to *Castor canadensis* [26–29], which demonstrates more building activity than *Castor fiber* [11,30]. Facing dynamic changes of *Castor fiber* populations in European lowlands, and related variable scales of ecosystem alterations caused by these species, the analysis over time revealed that the hydrological relevance of beaver ponds appears compulsory in long-term forest ecosystem management planning also in Europe. Knowledge on temporal stability of maintained and abandoned beaver ponds may also provide new insights to quantify the beaver's role in the enhancement of water storage capacity in the catchment scale. The importance of research perspectives on beaver-influenced hydrological processes of forested and agricultural catchments was highlighted in numerous studies [10,14,19,26]. In this regard, Poland appears to be an appropriate study site for research on temporal stability of the beaver's hydrological influence on riparian forest ecosystems, as in the beginning of the 20th century, where beavers were nearly extinct, and since then, a continuous (natural and reintroduction-enhanced) increase of population abundance has been observed. The most significant increase of European beavers was observed in Poland in the period 1970–2000, when the population expanded from some 300 to approximately 50,000–80,000 individuals [31]. Ever since the highest concentrations of beavers were observed in NE Poland, they have been centered primarily in the areas of Augustowska and Knyszyńska Forest.

The main goal of our study was to investigate the distribution, damming height, areas and volumes of ponds created by European beaver (*Castor fiber*) in the forest stream to reveal their temporal stability and importance in shaping the capacity of channel retention (the amount of water stored in the channel). We present a comparative study based upon the results of field investigations done in August 2006 (when at least five beaver families were settling in the valley of the study area) and in August 2013 (when three beaver families were present in the valley). Our study addresses the following questions: (i) how has the retention volume of beaver ponds in the riparian forest landscape changed in 7 years of decreasing construction activity of beavers? (ii) how stable over time are beaver ponds as water reservoirs? (iii) have hydrological conditions of abandoned beaver ponds' ecotones changed as a result of their abandonment by beavers? and (iv) to what extent is the beaver's role in shaping water storage and ecosystem services in the riparian forest landscape? The conclusions we derived from our study may be used in the decision making of forest water management by providing trade-off analysis of the beaver's role in riparian forests.

2. Materials and Methods

2.1. Study Area

Study was carried in the Krzemianka river valley located in the Knyszyńska Forest in NE Poland (Figure 1). Krzemianka is a lowland stream of 9.2 km length. Area of the watershed reaches nearly 32 km^2, of which almost 80% remain forested. Width of the river seldom exceeds 4 m and the average depths reach 0.2–0.5 m. Slope of the river equals 0.46%. Fragments of the river course flowing through the forests remain natural and only certain parts of the river flowing through the agricultural lands (mostly meadows) were regulated. Average momentary discharge of the river reaches 0.12 m^3/s [32].

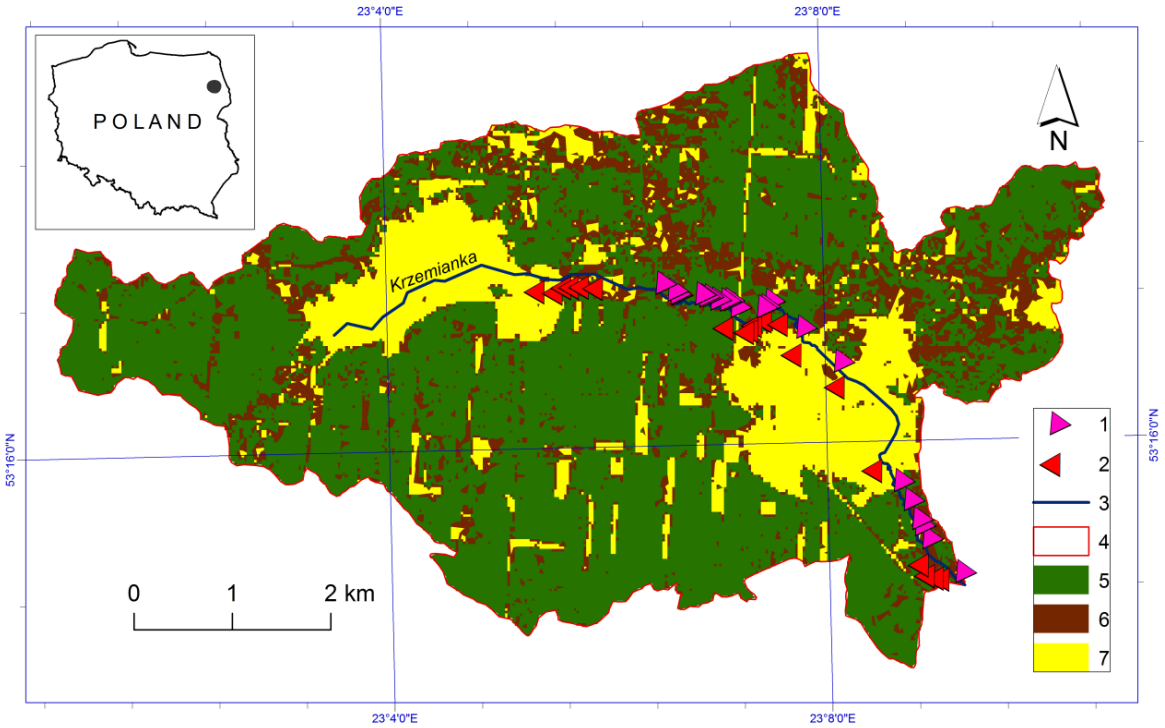
The area of research due to exceptional hydrological features such as numerous springs and natural landscape of the river valley and the occurrence of riparian alder forests (dominant species are *Alnus glutinosa*, *Betula* sp. and *Picea abies*) is covered by protection and remains both a natural reserve and Natura 2000 site. The population of beaver in the Krzemianka river valley has been steadily increasing since the 1950s to some 25 individuals (five families) in 2005–2006. Since then, due to natural ecological feedbacks (abuse of food base in the close vicinities of the river) and anthropogenic pressures (attempts to destroy beaver dams), the number of beaver in the Krzemianka river valley has constantly decreased to reach the stability of some 10–12 individuals, divided into three families in 2013.

2.2. Field Investigation

Beaver ponds in the Krzemianka river valley were investigated in August 2006 and August 2013. Every active beaver dam (that dammed the water levels of the river) was recorded and its damming height (difference in the water level upstream and downstream of the dam), area of the beaver pond, and the average and maximum depths of each pond were also measured with measuring tapes and geodetic instruments. The location of particular dams and ponds was recorded with a GPS. Investigations in 2006 and 2013 were done during almost the same water level (0.02 m difference),

measured in the water gauge profile located 80 m upstream of the confluence of Krzemianka to the river Czarna.

Figure 1. Study area, catchment of Krzemianka River. 1. Location of beaver ponds in 2006; 2. Location of beaver ponds in 2013; 3. River Krzemianka; 4. Boundaries of the catchment; 5. Dry land forests; 6. Riparian forests; 7. Meadows and arable lands.



3. Results

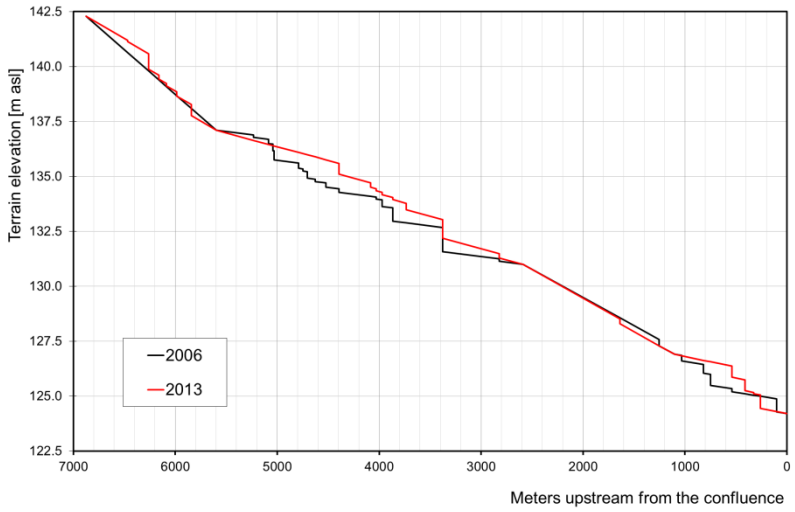
Field investigation in the valley of Krzemianka revealed the decline of construction activity of beavers in 2013 compared to 2006 (Table 1). Although only a small decrease in the number of beaver ponds was observed (in August 2006, 22 beaver ponds were recorded; in August 2013, 19 beaver ponds), the average, maximum and summarized volumes and areas of beaver ponds (considered as reservoirs with open water table), as well as the total damming height of the cascade of ponds, decreased significantly. In 2006, construction activity of beavers was reflected by the occurrence of beaver dams, where the total water storage capacity of the river channel reached approximately 15,000 m^3 and the total damming height of beaver pond cascade equaled 6.6 m. In 2013, the total retention of beaver ponds in the valley of Krzemianka reached approximately 7000 m^3 along with the damming height of the cascade, equaling 5.6 m (Table 1; Figure 2). The damming height of the single average beaver dam in the Krzemianka river valley remained similar in both the years 2006 and 2013, reaching 0.3 m approximately. A larger number of beaver followed their high construction activity in 2006, which resulted in an occurring sequence of beaver dams, of which the highest dammed water level was approximately 1.1 m, whilst in 2013, when the number of beavers and their activity declined, the highest damming level of the largest beaver pond reached 0.9 m. The volume of the average beaver pond in the valley of Krzemianka in 2006 equaled 680 m^3, almost doubling the average volume of

beaver pond in 2013, when this value reached 370 m^3. Similarly, the maximum volume of a single beaver pond was more than twice as high in 2006 (4550 m^3) as in 2013 (2000 m^3). The area of an average beaver pond has decreased nearly three times in the analyzed time period (from 890 m^2 in 2006 to 320 m^2 in 2013), but the total area of beaver ponds decreased significantly (from over 4.6 ha in 2006 to approximately 0.6 ha in 2013) (Table 1). A vast decrease of the average area of beaver ponds observed since 2006–2013, along with comparable average damming heights reaching 0.3 m in both 2006 and 2013, allows one to suspect that the most important hydromorphological changes occurred in the marginal zones of beaver ponds (where beaver ponds are the shallowest).

Table 1. Comparison of selected statistics of beaver ponds in Krzemianka river valley in 2006 and 2013.

Statistic	2006	2013
No. of beaver ponds	22	19
Total volume of ponds (m^3)	15,000	7000
Total damming height of the cascade (m)	6.6	5.6
Avg. damming height (m)	0.3	0.3
Max. damming height of a single dam (m)	1.1	0.9
Avg. volume of ponds (m^3)	680	370
Max. volume of a single pond (m^3)	4550	2000
Avg. area of beaver ponds (m^2)	890	320
Total area of beaver ponds (m^2)	46,300	6080
Max. area of beaver pond (m^2)	13,000	350

Figure 2. Longitudinal profile of the first 7 km of the Krzemianka River in 2006 and 2013 (distance measured from the confluence of Krzemianka).

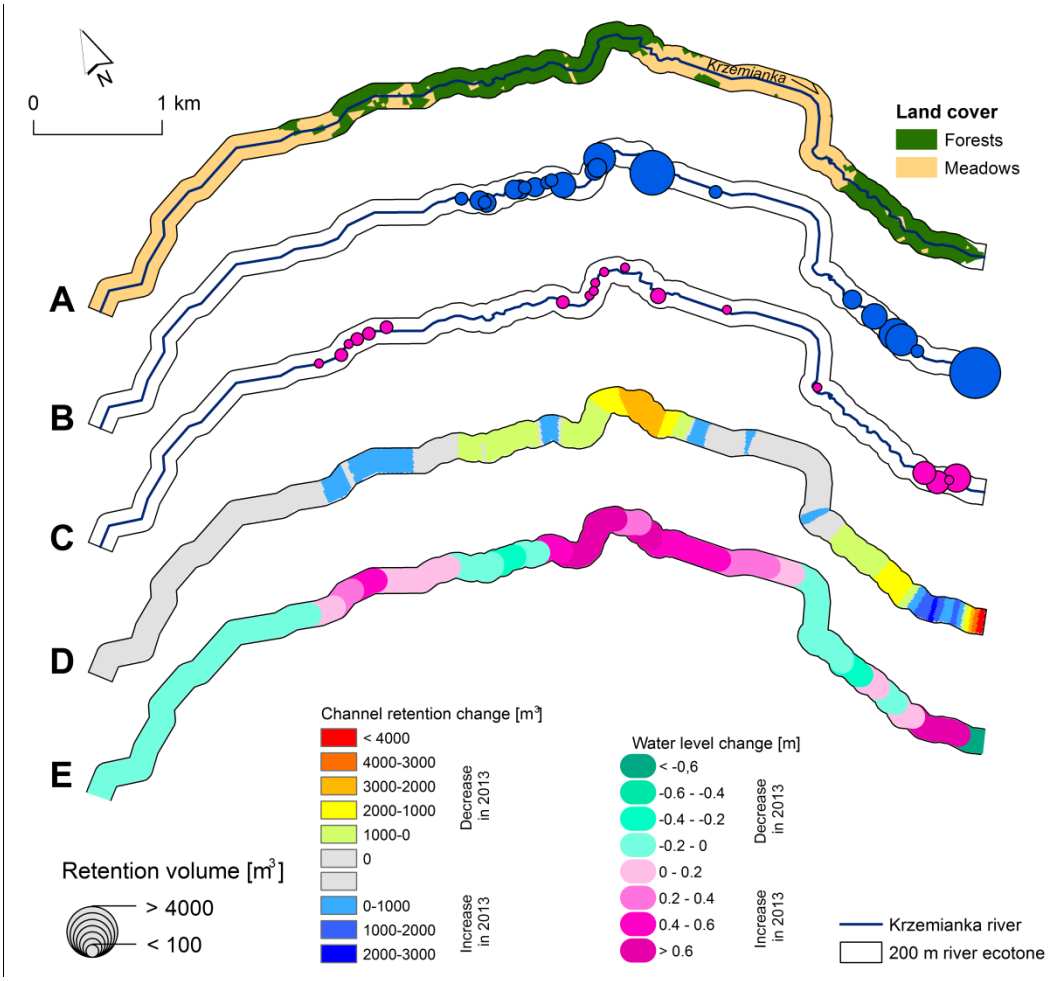


In 2006, the activity of beavers was mostly limited to forested areas. Although in 2013 the construction activity of beaver decreased in the area analyzed, their expansion to areas of drained meadows in the upper-most reach of the river Krzemianka was observed (Figure 3A–C). Only five beaver dams constructed in (before) 2006 maintained an active role in channel retention in 2013 (Figure 3B,C). Remaining dams and ponds that were constructed on or before 2006 did not play an

active role in channel retention of the river Krzemianka in 2013 (beaver dams have either been destroyed or have not dammed water). As only three out of the 19 beaver ponds present in the valley of Krzemianka in 2013 were freshly maintained by beaver, one can conclude that 11 beaver dams were constructed and later abandoned by beavers in the succeeding years 2007–2012. This observation allows the statement that the average period reaches approximately 5 years, in which the abandoned beaver ponds have remained functioning as an object inducing channel retention (and thus active water storage and related ecohydrological processes in aquatic habitats).

Due to the abandonment of ponds by beaver, channel retention in a river decreased in approximately half of the river length (Figure 3D). However, at the same time, the general increase of water levels in the river was observed, especially in the reaches passing through forests (Figure 2, Figure 3E).

Figure 3. **A**—land cover of the 200 m ecotone of Krzemianka river; **B**—distribution of beaver ponds and their retention capacities in August 2006; **C**—distribution of beaver ponds and their retention capacities in August 2013; **D**—channel retention change (2013 comparing to 2006); **E**—water level change (2013 comparing to 2006).



Such an observation allows the conclusion that, although the channel retention of Krzemianka has been steadily decreasing since 2006, riparian wetlands that have developed as a result of increased sedimentation in beaver ponds within the reaches abandoned by beavers still play an important role in water storage. In these zones, channel retention has been taken over by groundwater storage. As a

result, groundwater levels keep rising and induce high saturation of the habitats of the riparian forests. Within riparian forest stands, despite the decreasing activity of beaver, the increase of water levels by up to 0.6 m was observed (Figure 3E).

Such an observation concludes that although the number of beavers examined in the river valley decreased along with the channel retention in the succeeding years 2006–2013, abandoned beaver ponds that serve as newly created riparian wetlands induced an increase of water storage (and water levels) at the local scale. Some changes in forest structure (such as the ones recorded in the largest beaver pond surveyed, located just upstream of the confluence of the river Krzemianka to the river Czarna) resulted in the appearance of canopy gaps (Figure 4), entailed by the permanent inundation and dying off of trees in the riparian forest, which seemed to speed-up the process of macrophyte development as a result of enhanced light penetration to the bottom parts of the forest.

This process can be managed by appropriate forest policy, as not all of the dead trees must be removed immediately once the first syndromes of negative reaction of forest stands to inundation were noticed.

4. Discussion

In the study presented, we observed that both increased sedimentation rates and increased development of aquatic and riparian macrophytes in marginal zones of beaver ponds induced a loss of channel retention and an increase of the wetland riparian zone in approximately the 5 years since the pond was abandoned by beaver. In the analyzed example, we observed a general increase of water levels in habitats transformed by beaver, and we conclude that approximately 50% of the initial volume of the channel retention of freshly constructed and maintained beaver ponds has been transformed in the succeeding 7 years analyzed into water retention in soil and ground (wetlands). Retention of water in newly developed wetland habitats is much more constant over time than channel retention, being at the same time much less vulnerable to external disturbances such as beaver dam removal. Considering soil porosity, the debris and roughness of wetlands that have been recently developed in marginal zones of abandoned beaver ponds, one can conclude that the total retention capacity of a cascade of beaver ponds (immediately after their construction) can be considered as a quantitative proxy of the total dimension of beaver's influence on water retention in the catchment scale. In this regard, channel retention decreased because of the decreasing numbers and activity of beaver, while the natural retention of water in the riparian forest habitats increased and remained constant over time. Such observations conclude that the cascades of beaver ponds are a natural, efficient and long-term means of increased water retention in forested catchments.

The value of maximum possible retention capacity of beaver ponds' cascade can be therefore considered an ecosystem service supplied by these rodents. On the basis of the available research results and methodologies [33,34], while bearing in mind the economic circumstances of technical measures applied to increase water retention in forests of Poland, we estimate that the annual value of water storage enhanced by beavers in the valley of Krzemianka reached some €4000 per annum, which results in the approximate total value of €87,000, if the depreciation rate was included in the analysis [35].

Figure 4. Landscape of the biggest beaver pond in the Krzemianka river valley in 2006 (**A**) and in 2013 (**B**). Pictures present views from the same position. Photo: Andrzej Grygoruk and Mateusz Grygoruk (Grygoruk, 2008 [15]).

Although the construction activity of these rodents decreased in the 7 years analyzed and the majority of the ponds were abandoned by beaver, the damming height of the average beaver dam remained nearly the same (Table 1). Therefore, river continuum, even when the beaver dams were not being sustained by beaver, remained fragmented. This phenomenon can significantly interfere with the management of ichtyofauna of forest streams settled (abandoned) by beaver, as the migrations of fish may suffer from permanent damming, even long after beaver have left the riparian forest ecosystem [25,36,37]. This process, as well as the loss of trees as a result of the foraging activity of beaver, should remain a consideration for the trade-off of increased water retention.

Beaver-related hydromorphological modifications of river ecotones in forest landscapes, followed by the development of new wetland habitats that efficiently store water are strongly desirable from the point of view of Water Framework Directive implementation [38]. We revealed that although the hydrological role of beaver ponds in riparian ecosystems changes as a result of the abandonment of ponds by beaver, long term consequences of beaver-related increases of water storage remain significant in a catchment scale from a long term perspective.

5. Conclusions

Beaver dams that were not maintained by beaver for some 3–5 years have lost their capability to play an active role in shaping channel retention. The total volume of channel retention induced by beaver decreased from nearly 15,000 m^3 (measured in the year of high construction activity of beaver) to only 7000 m^3 (measured in the year of low concentration of beaver in the area analyzed). The average volume of beaver ponds in the analyzed example decreased from 680 m^3 in 2006 to some 350 m^3 in 2013. Although active storage volumes of particular beaver ponds decreased by 50% on average, water levels in the river and adjacent habitats, especially in river stretches located in the forests (where beaver heavily modified hydromorphological features of the stream), increased by 0.48 m on average for the case analyzed. In locations where beaver activity was limited by constraints of environmental origin (lack of trees in close vicinity of the river channel) or human-enforced pressures (removal of beaver dams), water levels in 2013 compared to 2006 remained nearly equal. This shows a relatively high potential influence of beaver for saturation of riparian forest habitats and relatively little influence of beaver on arable lands and meadows located in the examined river valley. Beaver ponds that went unmaintained for at least 5 years still induced an increase of groundwater levels in adjacent habitats, although they did not play a significant role in channel retention. Hence, although the channel retention of beaver ponds that was not maintained by beaver decreased significantly, the total water storage capacity of newly developed wetlands appeared to remain a major long-term consequence of beavers' activity in the analyzed forest stream. This observation, although based on a relatively short-term data set, stays in accordance with the results of Butler [26] and Terwilliger and Pastor [39] who reported that ecological relevance of beaver ponds may last even tens of years after being abandoned by beavers.

In anticipating the role of beaver dams and ponds for the enhancement of channel retention capacity of small, temperate forest streams, one should assure the continuous presence of beavers within the site. Otherwise, the ongoing process of sedimentation, debris and plant encroachment in abandoned beaver ponds will entail a decreasing role of the small reservoirs in shaping channel retention of streams historically settled by beaver [3,5,11,13,14,16,18]. However, from a long term perspective, the total capacity of beaver ponds, along with the increased water levels in riparian forest habitats transformed and abandoned by beaver, provided a prerequisite of exceptional potential as a natural water retention capacity in a catchment scale [26]. The next steps to follow the presented research should include analysis of total valley storage capacity (channel retention and groundwater storage) in order to reveal the accurate quantity of water stored in wetlands and maintained by beaver, and to highlight the variable relevance of these rodents in shaping hydrological conditions of lowland, temperate forest streams.

The monetary value of the beaver-related increase of water retention in the riparian forest and Krzemianka river valley reached roughly €87,000 (€4000 per annum). This value should be considered as a balance of beaver-related losses, such as cut tree stands. A consideration for the monetary impact of the beavers' role in shaping channel retention, or wetland water retention as the important ecosystem service, could be used to change the stakeholder's perception of beaver and to ensure that the riparian forest is comprehensively balanced from an economic perspective while enhancing the implementation of a Water Framework Directive in forests. In this regard, we stress that Central European studies on beaver's role in forest ecosystems—so far dealing with multiple important aspects of biocenoses influenced by this rodent [1,10,21,40] combined with analyses of river hydromorphology and related aspects [25,41]—should continue, anticipating the longevity of beaver-induced changes in riparian biotopes favoring river restoration.

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Author Contributions

Mateusz Grygoruk supervised and conducted the data analysis and prepared the manuscript. Magdalena Nowak assisted in field investigation, data collection and assisted in manuscript preparation.

Conflicts of Interest

The authors declare no conflict of interest.

References and Note

1. Boczoń, A.; Wróbel, M.; Syniaiev, V. The Impact of Beaver Ponds on Tree Stand in a River Valley. *J. Water Land Dev*. **2009**, *13a*, 313–327.
2. Collen, P.; Gibson, R.J. The General Ecology of Beavers (Castor spp.), as Related to Their Influence on Stream Ecosystems and Riparian Habitats, and the Subsequent Effects on Fish—A Review. *Rev. Fish Biol. Fisher.* **2000**, *10*, 439–461.
3. De Visscher, M.; Nyssen, J.; Pontzeele, J.; Billi, P.; Frankl, A. Spatio-temporal Sedimentation Patterns in Beaver Ponds along the Chevral River, Ardennes, Belgium. *Hyd. Proc.* **2014**, *28*, 1602–1615.
4. Harthun, M. The Influence of the European Beaver (*Castor fiber albicus*) on the Biodiversity (Odonata, Mollusca, Trichoptera, Ephemeroptera, Diptera) of Brooks in Hesse (Germany). *Limnologica* **1999**, *29*, 449–464.
5. Harthun, M. Influence of the Damming-up by Beavers (*Castor fiber albicus*) on Physical and Chemical Parameters of Highland Brooks (Hesse, Germany). *Limnologica* **2000**, *30*, 21–35.

6. Hering, D.; Gerhard, M.; Kiel, E.; Ehlert, T.; Pottgiesser, T. Review Study on Near-natural Conditions of Central-European Mountain Streams with Particular Reference to Debris and Beaver Dams: Results of the "REG Meeting" 2000. *Limnologica* **2001**, *31*, 81–92.
7. Naiman, R.J.; Melillo, J.M.; Hobbie, J.E. Ecosystem Alteration of Boreal Forest Streams by Beaver (*Castor canadensis*). *Ecology* **1986**, *67*, 1254–1269.
8. Naiman, R.J.; Pinay, G.; Pastor, J.; Johnston, C.A. Beaver Influences on the Long-term Biogeochemical Characteristics of Boreal Forest Drainage Networks. *Ecology* **1994**, *75*, 905–921.
9. Nyssen, J.; Pontzeele, J.; Billi, P. Effect of Beaver Dams on the Hydrology of Small Mountain Streams: Example from the Chevral in the Ourthe Orientale Basin, Ardennes, Belgium. *J. Hydrol.* **2011**, *402*, 92–102.
10. Pęczuła, W.; Szczurowska, A. Long-term Changes in Phytoplankton in a Humic Lake in Response to the Water Level Rising: The Effects of Beaver Engineering on a Freshwater Ecosystem. *Knowl. Manag. Aquat. Ecosyst.* **2013**, *410*, doi:10.1051/kmae/2013061.
11. Rossel, F.; Bozser, O.; Collen, P.; Parker, H. Ecological Impact of Beavers *Castor fiber* and *Castor canadensis* and Their Ability to Modify Ecosystems. *Mammal Rev.* **2005**, *35*, 248–276.
12. Burns, D.A.; McDonnell, J.J. Effects of Beaver Pond on Runoff Processes: Comparison of Two Headwater Catchments. *J. Hydrol.* **1998**, *205*, 248–264.
13. Butler, D.R.; Malanson, G.P. Sedimentation Rates and Patterns in Beaver Ponds in a Mountain Environment. *Geomorphology* **1995**, *13*, 255–269.
14. Green, K.C.; Westbrook, C.J. Changes in Riparian Area Structure, Channel Hydraulics and Sediment Yield Following Loss of Beaver Dams. *Br. Columbia J. Ecosyst. Manag.* **2009**, *10*, 68–79.
15. Grygoruk, M. Metodyka szacowania objętości retencyjnej stawów bobrowych oraz ich oddziaływania na stosunki wodne zlewni leśnych. *Stud. i Mat. CEPL* **2008**, *10*, 162–172.
16. Gurnell, A.M. The Hydromorphological Effects of Beaver Dam-Building Activity. *Prog. Phys. Geog.* **1998**, *22*, 167–189.
17. Hill, A.R.; Duval, T.P. Beaver Dams along an Agricultural Stream in Southern Ontario, Canada: Their Impact on Riparian Zone Hydrology and Nitrogen Chemistry. *Hyd. Proc.* **2009**, *23*, 1324–1336.
18. John, S.; Klein, A. Hydrogeomorphic Effects of Beaver Dams on Floodplain Morphology: Avulsion Processes and Sediment Fluxes in Upland Valley Floors (Spessart, Germany). *Quaternaire* **2004**, *15*, 219–231.
19. Tornblom, J.; Angelstam, P.; Hartman, G.; Henrikson, L.; Sjoberg, G. Toward a Research Agenda for water policy implementation: Knowledge about Beaver (*Castor fiber*) as a tool for water Management with a Catchment Perspective. *Balt. For.* **2011**, *17*, 154–161.
20. Woo, M.K.; Waddington, J.M. Effects of Beaver Dams on Subarctic Wetland Hydrology. *Arctic* **1990**, *43*, 223–230.
21. Halley, D.; Rossel, F.; Saveljev, A. Population and Distribution of Eurasian Beaver (*Castor fiber*). *Balt. For.* **2012**, *18*, 168–175.
22. Nummi, P.; Kuuluvainen, T. Forest Disturbance by an Ecosystem Engineer: Beaver in Boreal Forest Landscapes. *Boreal Environ. Res.* **2013**, *18*, 13–24.

23. Boczoń, A.; Wróbel, M.; Syniaiev, V. The Impact of Beaver Ponds on Water Resources in the Catchment Area in the Browsk Forest Disctrict—A Case Study. *For. Res. Pap.* **2009**, *70*, 363–371.
24. Żurowski, W. Building Activity of Beavers. *Acta Theriol.* **1992**, *37*, 403–411.
25. Burchsted, D.; Daniels, M.; Thorson, R.; Vokoun, J. The River Discontinuum: Applying Beaver Modification to Baseline Conditions for Restoration of Forested Watersheds. *BioScience* **2010**, *60*, 908–922.
26. Butler, D.R. Characteristics of Beaver Ponds on Deltas in a Mountain Environment. *Earth Surf. Process. Landf.* **2012**, *37*, 876–882.
27. Butler, D.R.; Malanson, G.P. The Geomorphic Influences of Beaver Dams and Failures of Beaver Dams. *Geomorphology* **2005**, *71*, 48–60.
28. Meentemeyer, R.K.; Butler, D.R. Temporal and Spatial Changes in Beaver Pond Locations, Eastern Glacier National Park, Montana, USA. *Geogr. Bull.* **1995**, *37*, 97–104.
29. Meentemeyer, R.K.; Butler, D.R. Hydrogeomorphic Effects of Beaver Dams in Glacier National Park, Montana. *Phys. Geog.* **1999**, *20,* 436–446.
30. Danilov, P.I. Canadian and European Beavers in Russian Northwest (Distribution. Number, Comparative Ecology). In Proceedings of the Third Nordic Beaver Symposium, Iiomats, Finland, 15–17 September 1992; Ermala, A., Lahti, S., Eds.; Finnish Game and Fisheries Research Institute: Helsinki, Finland.
31. Borowski, Z. Distribution, Abundance and Damages Caused by European Beavers in Polish Forests; Available online: http://www.efinord.efi.int/files/attachments/efinord/forest_and_water_palanga_1-3_oct.2013/zbigniew_borowski_-_beaver_in_poland.pdf (accessed on 30 April 2014).
32. Grygoruk, M. Evaluation of Beaver Dams and Ponds Influence on Water Circulation in Forest Catchment. Master Thesis, Department of Hydrology, Faculty of Geography and Regional Studies, University of Warsaw, Warsaw, Poland, 2007.
33. Grygoruk, M.; Mirosław-Świątek, D.; Chrzanowska, W.; Ignar, S. How Much for Water? Economic Assessment and Mapping of Floodplain Water Storage as a Catchment-Scale Ecosystem Service of Wetlands. *Water* **2013**, *5*, 1760–1779.
34. Tyszka, J. Estimation and Economic Valuation of the Forest Retention Capacities. *J. Water Land Dev*. **2009**, *13a*, 149–159.
35. The monetary value of water storage calculated on the basis of sums spent on construction and maintenance of small water retention reservoirs in forests has to be calculated in accordance with economic basis, including the depreciation. The values of depreciation reaching 4% per annum were assumed in water retention reservoirs in NE Poland. The methodology and assumptions are presented in the paper of Grygoruk *et al*. [33].
36. Smith, J.M.; Mather, M.E. Beaver Dams Maintain Fish Biodiversity by Increasing Habitat Heterogeneity throughout a Low-Gradient Stream Network. *Freshw. Biol.* **2013**, *58*, 1523–1538.
37. Lokteff, R.L.; Roper, B.B.; Wheaton, J.M. Do Beaver Dams Impede the Movement of Trout? *Trans. Am. Fish Soc.* **2013**, *142*, 1113–1125.
38. Futter, M.N.; Keskitalo, E.C.H.; Ellison, D.; Pettersson, M.; Strom, A.; Andersson, E.; Nordin, J.; Löfgren, S.; Bishop, K.; Laudon, H. Forests, Forestry and the Water Framework Directive in Sweden: A Trans-Disciplinary Commentary. *Forests* **2011**, *2*, 261–282.

39. Terwilliger, J.; Pastor, J. Small Mammals, Ectomycorrhizae, and Conifer Succession in Beaver Meadows. *Oikos* **1999**, *85*, 83–94.
40. Miszczuk, H.; Oglęcki, P. The Estimation of European Beaver Community in the Osownica River Catchment Area. *Sci. Rev. Eng. Env. Sci.* **2004**, *29*, 179–191.
41. Sawa, K.; Popek, Z. Analysis of the Connections between Hydromorphological Conditions and Biocenotic Diversity on the Example of the Zwoleńka River. *Ann. Warsaw Univ. Life Sci. SGGW Land Reclam*. **2011**, *43*, 173–184.