To store or to drain - to lose or to gain? Rewetting drained peatlands as a measure for increasing water storage in the transboundary Neman River Basin

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Abstract

Agriculture continues to place unwanted pressure on peatland functionality, despite international recognition calling for their conservation and restoration. Rewetting of peatlands is often the first step of restoration that aims towards improving the delivery of ecosystem services and their benefits for human well-being. Ongoing debates on peatland restoration in agricultural landscapes raise several issues based on the valuation of benefits achieved versus the costs of peatland restoration. Using the transborder Neman River Basin in North-Eastern Europe, this study aimed to quantify and evaluate the gains provided by peatland rewetting. To achieve this, this study estimated i) possible changes in water storage capacity from peatland restoration, ii) the value of expected benefits from restoration

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and iii) costs of restoration measures at the overarching basin level. Applying multiple assumptions, it was revealed that rewetting drained peatlands in the Neman River Basin could increase water retention by 23.6-118 M m^3. This corresponds to 0.14-0.7% of the total annual Neman River discharge into the Baltic Sea. Unit increase of water retention volume due to rewetting ranged between 69 and 344 $m^3 \cdot ha^{-1}$. The estimated water retention value ranged between 12 and 60.2 M EUR · $year^{-1}$. It was also shown that peatland rewetting at the scale of Neman River Basin would cost from 6.8 M and 51.5 M EUR · $year^{-1}$ depending on the selected scenario. Applying less expensive rewetting measures (non-regulated outflow from ditch blocks), the economic gains (as water storage ecosystem service of rewetted peatlands) from rewetting exceed the costs of rewetting. Thus, rewetting peatlands at a river-basin scale can be considered technically and economically efficient measures towards sustainable management of agricultural landscapes. The novel methodology applied in this study can be used when valuing trade-offs between the rewetting of drained peatlands and leaving them drained for the uncertain future of wetland agriculture.

Keywords: wetlands, ecosystem services, fen, bog, retention, restoration.

1. Introduction

Over the years, land use change, peat extraction and intensification of agriculture and forestry have caused loss and degradation of peatlands across the globe, mainly due to ditching and drainage of peatlands area (Glina et al., 2018; Harpenslager et al., 2015; Jones et al., 2017; Luan and Wu, 2015; Urák et al., 2017). Throughout Europe, the drainage of peatlands for agricultural purposes exceeds 50% and is the main threat to carbon storage (Hatala et al., 2012; Loisel et al., 2021), biodiversity (Renou-Wilson et al., 2019), water retention and water quality, as well as eutrophication of water bodies (Grygoruk et al., 2015; Harpenslager et al., 2015). Countries of the former Soviet Union are excellent examples of the negative effect agricultural expansion and industrialization have had on peatlands (Povilaitis et al., 2015). Thus, the performance and functioning of peatlands have been severely impaired, resulting in many negative impacts including altered water flow regimes, disrupted carbon and nutrient cycles, change in vegetation cover and biodiversity (Gyimah et al., 2020; Lachance et al., 2005; Laine et al., 1995), land subsidence, increased flood and fire risk and reduced ecosystem resilience (Jaenicke et al., 2011; Glina et al., 2018). Considering the consequences of peatland degradation and climate change, paying more attention to peatland management and restoration issues at the river basin level is crucial. As most degraded peatlands are located in managed agricultural landscapes, solutions are required that promote practical measures to restore wetland ecosystems, deliver appropriate effects in their restoration and wise management, as well as provide measurable benefits to society, aside from the benefits gained from agriculture (Andersen et al., 2016; Grygoruk and Rannow, 2017).

The ongoing re-prioritizing of peatlands and mire management plans mainly for the enhancement and conservation of carbon-, nutrients- and water-storage capabilities, indicates that peatland restoration will soon be, if not already, one of the most frequently applied management measures (Gewin, 2020; Manton et al., 2021). Although restored peatlands may not provide a similar range of ecosystem services compared to pristine mires (Kreyling et al., 2021), the restoration of peatlands can provide a number of benefits such as increased water retention, nutrient removal, flood protection, carbon sequestration and storage, biodiversity and the prevention of peatland fires can be gained by restoration (Ahmad et al., 2020; Bourgault et al., 2017; Jabłońska et al., 2020; Kharanzhevskaya et al., 2020; Lane and D'Amico, 2010; Renou-Wilson et al., 2019; Tanneberger et al., 2020). However, the performance of these services is strictly dependent on the availability of water (Jones et al., 2017).

Therefore, peatland restoration through rewetting frequently forms the first significant step of the restoration process (Grand-Clement et al., 2015; IPCC, 2014; LaRose et al., 1997; Gottwald and Seuffert, 2005; Jarašius et al., 2015; Worrall et al., 2007). Rewetting aims at reversing the effects of degradation and bringing peatlands' conditions back to a more natural state (Jaenicke et al., 2011; Emsens et al., 2020, Tuittila, 2000). The most common peatland restoration measure is to block the drainage ditches with dams (made of peat, mineral soil, wood, plastic and other material), which ceases water runoff and allows the groundwater table to rise in a surrounding peatland (Elo et al., 2015; Jaenicke et al., 2011; Klimkowska et al., 2010; Querner and Povilaitis, 2009). Furthermore, initial conditions, hydrological processes and, consequently, the possible amount of stored water and responses to drainage and rewetting vary depending on peatland type. For example, sloping fens have drier peat (Ross et al., 2019) and they are more sensitive to ditching and groundwater fluxes than flat fens (Chimner et al., 2018; Planas-Clarke et al., 2020). Drainage of bogs, on the other hand, strongly destabilizes water tables, leading to rapid drying of the surface layer and changes in vegetation (Money and Wheeler, 1999).

Applying land-use policy, governance and planning, or the implementation of projects requires skills to navigate the complexity of interactions that consider landscapes as social-ecological systems (Angelstam et al., 2019). Indeed, hydrological processes are highly interconnected, and the loss of water storage at the basin level can cause severe disruption to social-ecological systems. Reducing vulnerability to water stress through integrated water resource management, including peatland conservation and restoration, is crucial for achieving sustainable social-ecological benefits (Huggins et al., 2022). Functioning peatlands provide resilience to water stress, whereas drained peatlands are subjected to reduced water storage, loss of peat thickness, land subsidence, loss of peatland area, land cover change and severed peatland functioning. Even though degraded peatlands once rewetted are not able to store as much water as pristine ones due to low peat thickness and porosity, they still positively affect water balance and act as flood protection (Liu et al., 2022). Although water availability in peatlands is the main factor that determines peatland functions, there is still little research on water storage itself, its importance and value. It is mostly only mentioned in the context of other ecosystem services provided by peatlands, such as carbon storage and nutrient retention, but all of those services are water-driven.

Due to the unique organic soil structure in wet peatlands, they can retain large amounts of water (Craft, 2016; Price et al., 2016) and therefore contribute to the increase of water retention at the basin scale. This aspect, although widely known, is often neglected as a driver for peatland restoration mainly due to (1) a lack of knowledge about the scale of water retention increases in rewetted peatlands and (2) the diverse effects peatland rewetting has on water resources at the basin scale. In addition, other factors, such as local physical and climatic conditions, can also be challenging to measure and strongly influence results. Nonetheless, current policies and land management goals aim at both the conservation of pristine and restoration of degraded sites toward becoming climate-neutral (European Commission, 2019). To achieve this, methods and tools are required that provide fundamental broadscale river basin analyses for decision-makers. Unfortunately, such methods are often missing. Effective procedures for presenting wetland restoration's social and economic benefits, which can become an effective means of persuasion that can influence politics and society, are also lacking. For example, what would be the estimated monetary cost versus benefit of rewetting all degraded peatlands within a river basin?

This paper focuses on quantifying and valuing water retention gained through rewetting of degraded peatlands in the Neman River Basin located in North-Eastern Europe. It was hypothesized that the benefit of peatland rewetting outweighs the cost of the restoration action at a river basin scale. This study aims to estimate i) possible changes in water storage capacity from peatland restoration, ii) the value of expected benefits from restoration and iii) the costs of restoration measures at the overarching basin level. Finally, an analysis of the cost-effectiveness of rewetting as a tool in modern wetland agriculture that can enhance soil carbon storage and sequestration, prevent adverse effects of climate change and improve the biodiversity of ecosystems impacted by agriculture on peatlands was provided.

2. Materials and methods

2.1. Study area

The Neman River Basin is located within the eastern part of the Baltic Sea Region. It spans across four countries: 47.7% of the basin in Lithuania, 46.4% in Belarus, 3.2% in Russia (Kaliningrad Oblast), 2.7% in Poland (Sileika et al., 2006; Rimkus et al., 2013; Stonevičius et al., 2017) (Fig. 1).

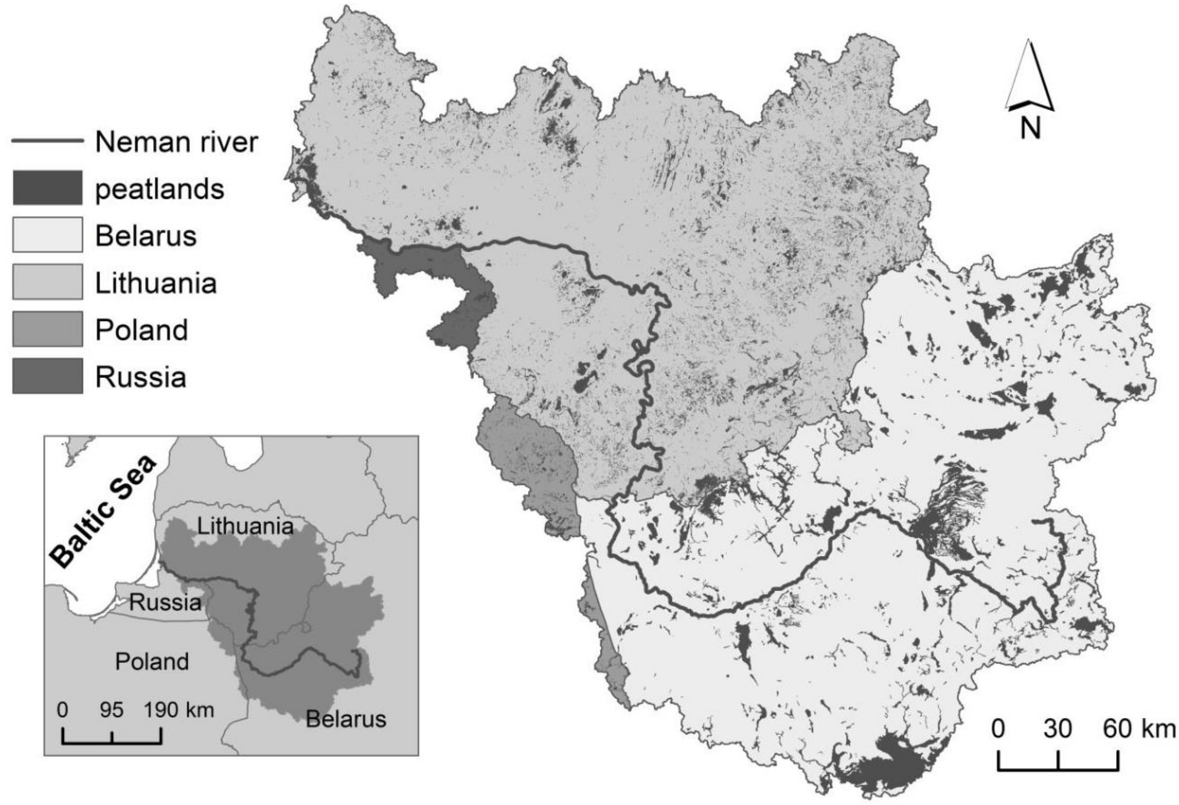

Figure 1. The peatlands in the Neman River Basin area (Neman River Basin is adapted from CCM River and Catchment Database © European Commission - JRC, 2007; peatlands adapted from the Peatlands of Neman Basin database: www.neman-peatlands.eu).

A negligibly small area of the Neman River Basin is also located in Latvia, but this share is too small (0.1%) to be presented in this study as a separate country. Depending on the source, the estimated total drainage area of the basin varies (Dubra et al., 2013). For the purpose of this study, the basin area of 95 753 km^2 was established on the basis of HELCOM data (CCM River and Catchment Database © European Commission - JRC, 2007), with the modification on the Polish part of the basin, using the Polish official hydrological data. Moreover, the HELCOM data implies that the drainage area of the Neman River does not cover any part of Latvia (Fig. 1). The Neman River (954 km total length) starts in Belarus and flows into the Curonian Lagoon, situated on the south-eastern coast of the Baltic Sea. The average annual discharge of Neman at the river mouth is 535 m^3/s (Glazaciovaite et al., 2012). The study area is located in a temperate climate zone with continental influences. Average annual air temperature in the basin is 6.8°C (Stonevičius et al., 2018), with average daily air temperatures amplitudes between the warmest and coldest months reaching 22–33°C (Dubra et al., 2013). The annual precipitation in the basin ranges from 520 to 900 mm (Rimkus et al., 2013) and based on the Global Average Annual Surface Runoff data computed for the years 1950–2000, the average annual surface runoff is 166 mm (Fekete et al., 2002). According to Stonevičius et al. (2017) and RCP2.6 and RCP8.5 projections, the mean annual temperature in the Neman River Basin, as well as the annual precipitation, will considerably increase in the future.

Despite the increase in precipitation, it was projected that the annual runoff would decrease by the end of the 21st century in both scenarios. According to future climate scenarios for the Neman River Basin, evapotranspiration will likely exceed precipitation from April to August. In large part of the basin, the climatic conditions during the summer season will gradually become subhumid (Stonevičius et al. 2017). Moreover, the effect of increased aridity might be amplified by a reduction in the spring flood runoff volume, and the timing of the spring flood may shift towards the beginning of the year. Shifts in the spring flood regime are likely to lead to a reduced base flow at the end of the 21st century. Thus, actions oriented at increasing water retention in the Neman River Basin using nature-based solutions such as peatland rewetting may be considered highly desirable and even indispensable, when analyzing water resources available for agriculture. MODIS-based Global Land Cover data indicates that the Neman basin is covered mainly by agricultural lands (68%) (Broxton et al., 2014). Thus, the interface of agriculture, water and the environment in the Neman basin seems to be the major challenge for sustainable management in the coming decades. Most of the basin is covered by sandy and clayey soils formed on residues deposited in the Saale and Weichselian glaciations (300 000 – 10 000 years B.C.). Peatlands developed throughout the Holocene and their depth is seldom

6 meters. Approximately 30% of the research area is covered by forests, consisting of mixed forests (24%) and coniferous forests (6%), as well some fragments of deciduous forests. Water and permanent wetlands cover approximately 0.4% of the basin. Grasslands and urban areas account for 0.2% and 0.6% of the basin, respectively.

2.2. Peatland mapping

Spatial data from the Peatlands of Neman Basin database (www.neman-peatlands.eu) was used, which was created in the framework of the project “DESIRE - Development of Sustainable (adaptive) peatland management by restoration and paludiculture for nutrient retention and other ecosystem services in the Neman River catchment” (Manton et al., 2021). The spatial database was created by firstly, compiling existing peatland data from Belarus (peatlands.by) and Lithuania (National Land Service under the Ministry of Agriculture of the Republic of Lithuania, 2020). However, as the Neman River Basin peatland data for Poland was outdated and not available for Russia’s Kaliningrad region, their peatlands were identified and mapped using remote sensing and subsequently traversed around with a GPS for ground verification. Subsequently, each polygon was attributed with information on protection status (protected planet.net), drainage status (Open street map) and landcover information (Broxton et al., 2014). The data was modified and analyzed using GIS software (ESRI ArcGIS platform). Initially, the raw peatland database consisted of a large number of polygons showing the distribution of peatlands in the research area (189 295 polygons). For the purpose of the study, it was necessary to correct the topology errors existing in the data (overlapping and bordering polygons with spatially mismatched boundaries).

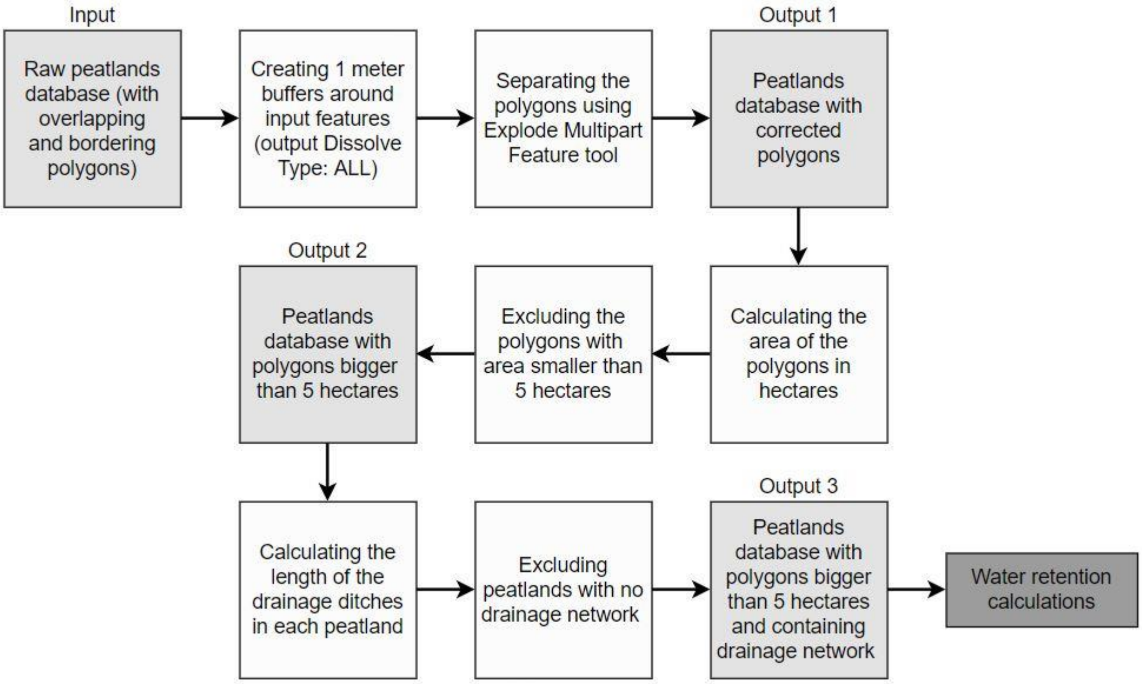

Figure 2. Scheme showing the process of peatlands database modification.

After the preliminary preparation, peatlands with an area smaller than 5 hectares (accounting for 109 997 ha in total) and not drained peatlands (in case of this study, with drainage density smaller than 10 meters/hectare, accounting for 17 905 ha in total) were excluded from the analysis. The final version of the database, ready for water storage calculations, consisted of 8885 polygons. The process of data preparation is shown in Figure 2.

2.3. Quantification of water storage capacity

Quantification of water storage capacity gained from the rewetting of peatlands can be a valuable tool for establishing management and restoration plans for these ecosystems (Jones et al., 2017). The damming of drains in peatlands is a common method used to rewet and improve water retention (Grygoruk et al., 2015; Jarašius et al., 2015). Therefore, a restoration scenario to peatlands impacted by drainage by blocking the ditches located in the peatlands area with dams was applied. Assuming that the diameter of the ditch does not change significantly with the amount of damming and the length of the ditch, the volume of water stored in the soil can be calculated using the linear approximation of the curves of unconfined groundwater table, using the effective porosity coefficient p (the ratio of storable water in the unit soil volume). Piling in the ditch has a limited range due to the occurring longitudinal slope of the ditch. Because the rules for the construction of damming devices assume the construction of a cascade (so that at the end of the range of impact of one damming device, the next one is placed), it was assumed that there is a possibility of damming up along the entire length of the ditches. Hence, the value of l can be taken as the length of all significant ditches. Taking into account the above-listed assumptions provided that the shape of a volume of stored water is a fraction of a cone (thus, b/2 and rp/3) and introducing additionally the coefficient a that takes into account that not every dam can have a damming device or may be inefficient (or destroyed), then the total volume of stored water, consisting of water retained in the ditch and water retained in the soil (Fig. 3.), was defined by the Formula 1 (Grygoruk et al., 2018):

$$V = ahl(b/2+rp/3) \qquad \text{(Formula 1.)}$$

where V is the water retained due to blocking the ditches with dams in m^3; a is the coefficient correcting the actual damming capacity on the ditch (dimensionless); h stands for the stacking (damming) height in m (hence, the value of h represents water level rise in a drainage ditch due to the use of a specific technical/nature-based facility capable to dam water in the ditch); l is a stacking (damming/backwater) range upstream in m, which stands for the length of the ditches that are within the boundaries of each peatland; b is the average width of the ditch in m; r is the average radius of water level rise in a cross-sectional view from the ditch in m, which refers to the maximum influence range that the ditch has on the water level rise and is dependent on the initial groundwater table, the soil type and the slope (Grygoruk et al., 2018); and p is the average soil porosity (dimensionless).

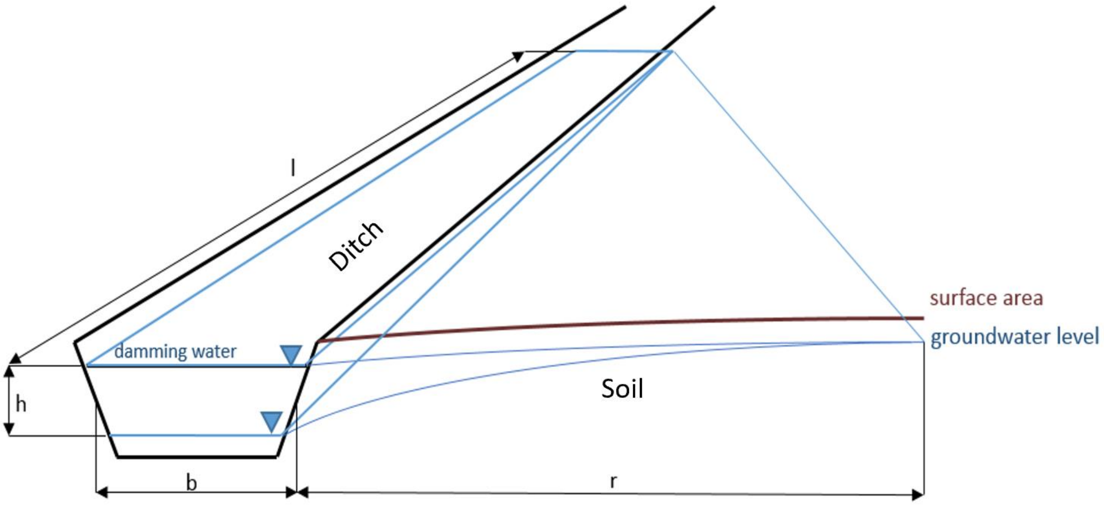

Figure 3. Variables of the Formula 1.: h stands for the stacking (damming) height in m; l is a stacking (damming/backwater) range upstream in m; b is the average width of the ditch in m; r is the average radius of water level rise in a cross-sectional view from the ditch in meters. Modified from Grygoruk et al. (2018).

To use this equation (Form. 1) to calculate the water storage capacity with such an extensive database, it was necessary to apply certain assumptions (Tab. A. in the Supplementary Material). To minimize the errors resulting from the assumptions made, it was necessary to determine the correction coefficient (a), which considers the possibility that some constructed dams may not be efficient and that it may not be possible to block all the ditches in the peatland. Although arbitrary, this value represents both the probable inefficiency of ditch block installations and the inappropriate design of ditch blocks (e.g., too few) that do not allow the ditch blocking systems to work with 100% efficiency (Grygoruk et al., 2018). This also incorporates a possibility that the rewetting by blocking ditches may not be effective due to lowered hydraulic conductivities of the drained peat (Succow and Joosten, 2001). However, most of the peatlands that were dealt with in the Neman River Basin tend to have dense networks of ditches, so the target zones of rewetting often overlap, making the rewetting feasible. This study's adopted coefficient value is 0.8 [-]. The calculations were performed in 2 different scenarios of the *r* value (20 and 50 meters) that represent the range of draining/rewetting influence of a ditch to adjacent peatland. The average width of the drainage ditches was assumed to be 2 meters and represents the average width of drainage ditches measured in the field during the field research campaigns in drained peatlands in the Neman River Basin in Lithuania (Amalvas Polder); Poland (Nietupa Valley) and Kaliningrad Region, Russia (Neman Delta). Average drainage depths represented by the average water table in the drained peatland were assumed to be 0.38 m below the ground level (bgl), an average value of groundwater depths measured in the field in the Amalvas Polder, Nietupa Valley and Neman Delta. According to Rezanezhad et al. (2016), peat soil porosity ranges from 71 to 95.1%.

Therefore, water retention calculations were carried out in 3 different peat porosity scenarios: 0.710, 0.951 and the obtained average value equal to 0.83. This value corresponds well to the porosity of the upper layers (30-35 cm) of long-drained histosols, which is between 0.82 and 0.86 (Brandyk and Szatyłowicz, 2002). Similar values ranged between 0.75 and 0.89 (average 0.84; n=75) were obtained for peat soils in the Neman R. Basin at the Amalvas, Skieblewo, and Nietupa sites (unpublished).

The topsoil will be responsible for water retention after peatland rewatering. The variability of peat porosity covers a wide range of different stages of peat development and decomposition that can be encountered in Neman River Basin. Based on the drainage network data, it was possible to calculate the length of the ditches (l) located within Lithuanian, Polish and Russian peatlands borders. These were calculated individually for each peatland polygon. Due to the lack of drainage network data and the broadscale size of peatlands for Belarus in the database, the average drainage density was calculated based on the length of the ditches in 20 representative peatlands located throughout the Belarusian agricultural landscape. According to the results the drainage density in Belarusian peatlands was 57 $m \cdot ha^{-1}$.

The calculations for water storage capacity were carried out in three scenarios, using different stacking heights: 0.1, 0.3 and 0.5 meters representing different possibilities of damming to be implemented with different measures (e.g., lower for the agricultural weirs, where farmers can regulate water levels; higher for constant ditch blocks that could be constructed of the peat and wood debris). Overall, the increase in water retention caused by blocking the ditches was calculated in 18 scenarios, using various values of the average radius of water level rise in a cross-sectional view from the ditch, porosity and stacking height. The algorithm applied in this study also considers the moisture of the peat before peatland rewetting, as well as provides multiple scenarios that produce results for different hydrological and soil conditions.

The calculations include only drained peatlands located in the Neman River basin. The applied restoration scenarios imply that the ditches within the boundaries of each drained peatland were blocked with dams. Thus, results will indicate the possible increase of water retention at the basin scale that can be reached by implementing the restoration measures to degraded peatlands in the Neman basin. The application of this approach allowed us to calculate (1) the number of dams needed to rewet the peatlands in the Neman Basin and (2) the total volume of water that could be retained in rewetted peatlands.

2.4. Valuation of water retention

The value of water storage in peatlands was estimated in monetary units in EUR $\cdot$ m^{-3} $\cdot$ $year^{-1}$, by applying the approach of Grygoruk et al. (2013), who provided a similar analysis for the floodplain wetland of the Biebrza Valley, which is a headwater part of Vistula Valley in Poland, which is located directly adjacent to the southern border of the Neman River Basin. The average water retention value was calculated as the average costs of design and construction of artificial water reservoirs divided by the total volume of these reservoirs and multiplied by the depreciation rate (Form. 2).

$$S_{val} = [\Sigma(Rc+M)/\Sigma Rv] \cdot Dr^{-1} \qquad \text{(Formula 2.)}$$

where *Sval* stands for a unit value of water storage [EUR $\cdot$ m^{-3} $\cdot$ $year^{-1}$], Rc stands for the total sum of expenses spent on the design and construction of a reservoir [EUR], M stands for maintenance costs (in this study this value was assumed to be equal to 0 as no information could have been obtained in this field), Rv stands for the total volume of the reservoir [m^3] and Dr stands for the annual depreciation rate [-]. Similar approaches were already applied in a number of other studies and have proven to be a reliable approach in a broad-scale analyses (Szałkiewicz et al., 2018). The available data on the existing reservoirs was collected, in which their principal purpose was to retain water. To keep the representativity of data, the goal was to find reservoirs located in different countries within the Neman basin, preferably constructed in different years. The study attempted to search for the official sources of data on the name of the reservoir, year of construction, coordinates, the total volume of water stored in the reservoir and original construction costs (in case the reservoir was constructed in the past, in different monetary systems). In the next step, the original values of reservoirs' construction were recalculated using the inflation rates and conversions of currencies, and – finally – expressed in Euro. Due to the lack of information on the management and maintenance costs of the reservoirs, they were not included in the analysis. Hence, one could assume that the final unit value of water retention remains a conservative estimate.

2.5. Quantification of restoration costs

The costs of rewetting drained peatlands were assessed on the basis of available data on rewetting actions. The scenario applied in this study assumes that the drainage ditches located within peatlands in the Neman River Basin are blocked with dams placed every 0.2 m in the slope decline. The durability and lifespan of a ditch block – similarly to the depreciation rate of a dam - was assumed as 40 years equal to a depreciation rate of 2.5% per annum, which is typical for hydrotechnical installations in the EU (Szałkiewicz et al., 2018). Average construction costs of a single dam (peat and wooden dam) were derived from the actual costs of these actions performed in Belarus, Lithuania and Poland, where one action was considered a single investment (e.g., one ditch block) of a particular type (e.g., wood dam; peat dam). To represent a range of possibilities in applying of peatland rewetting, three different scenarios of damming costs resulting from different types of actions were adopted for the calculations. In scenario A, the average cost of peat dams and wooden dams was used assuming that all ditches are small (max 2.0 m in width). In scenario B, the average cost of peat dams and wooden dams was used assuming that half of the ditches are wider (max 4.0 m in width). In scenario C, it was assumed that the cost of each dam is equal to the average cost of all of the actions applied in the examples covered by the analysed peatland rewetting projects, assuming at the same time that the size of all ditches was ‘average’. Since most of the analysed actions have been implemented in 2020 and 2021, these values were not recalculated as their inflation rates were considered to be similar. At the last stage, the values of water retention gained from rewetting with restoration costs were compared to determine whether the probable implementation of peatland restoration remains a cost (with no return rate) or an investment (with the return rate over a specific time).

3. Results

3.1 Peatlands of the Neman River basin and water storage capacity

The total area of peatlands in the Neman River basin is 1 006 802 hectares (neman-peatlands.eu). According to the methodological assumptions, peatlands less than 5 ha were not considered in calculations. Hence, the final area of peatlands considered in the rewetting analysis equaled 425 000 ha. After rewetting, water storage capacities varied due to the different drainage densities of peatlands and the applied scenarios of the average radius of water level rise in a cross-sectional view from the ditch, porosity and stacking height. With the scenario where $r = 50$ m and $p = 0.83$, when the stacking height equaled 0.1 meter, the volume of water retained on one hectare of peatland after the restoration ranged from 12 to 439 $m^3 \cdot ha^{-1}$, with a mean value of 69 $m^3 \cdot ha^{-1}$. When the applied stacking height was 0.3 meter, water storage ranged from 36 to 1 317 $m^3 \cdot ha^{-1}$ with a mean value of 207 $m^3 \cdot ha^{-1}$. With a stacking height of 0.5 meter, the volume of water stored in restored peatlands ranged from 59 to 2 196 $m^3 \cdot ha^{-1}$, with a mean value of 344 $m^3 \cdot ha^{-1}$ (Tab. 1, Fig. 4).

Table 1. Minimum, maximum, mean and median values of retained water volume for different stacking heights (when r = 50 m and p = 0.83)

Stacking height [m]	**Retained water volume [$m^3 \cdot ha^{-1}$]**				**Retained water volume [m^3]**			
	Min	Max	Mean	Median	Min	Max	Mean	Median
0.1	12	439	69	65	31	2 825 075	2 656	441
0.3	36	1 317	207	195	94	8 475 224	7 967	1 323
0.5	59	2 196	344	325	157	14 125 373	13 278	2 205

Asymmetric distributions of results with average values much higher than top whiskers are caused by the presence of several extensive peatlands located in the Neman basin, which also explains such a big difference in mean and median values. The total retained water volume in each peatland ranged from 31 to 2.8 M m^3 when the applied stacking height was 0.1 meter, from 94 to 8.5 M m^3 when the stacking height was 0.3 meter and from 157 to 14.1 M m^3 when the stacking height was 0.5 meter. The average volume of water retained in restored peatlands was 2 656 m^3, 7 967 m^3 and 13 278 m^3, respectively for 0.1, 0.3 and 0.5 meter stacking height values (r = 50 m and p = 0.83 scenario) (Tab. 1, Fig. 4). The total volume of water retention in the Neman River Basin that depends on the variant assumed in the calculations varies from 23.6 M m^3 when the stacking height equaled 0.1 m, through 70.8 M m^3 (stacking height 0.3 m) up to 118 M m^3 (stacking height 0.5 m) (r = 50 m and p = 0.83 scenario).

When compared to the total annual runoff volume of Neman River (16871.76 M m^3), these estimated values suggest that rewetted peatlands can potentially store between 0.14 up to 0.7% of total annual river runoff. This can be considered a high gain compared to water retention of artificial ponds and reservoirs.

Retained water volumes per hectare of a rewetted peatland varied, similarly, between scenarios analyzed (Fig. 4). On average of all the scenarios, rewetting of 1 ha of 'average drained peatland' in the Neman Basin equaled 149 $m^3 \cdot ha^{-1}$. The median value of water stored in peatlands due to rewetting equaled 100 $m^3 \cdot ha^{-1}$. The average maximum value of water that can be stored in a rewetted peat soil in the most optimistic rewetting scenario reached 344 m^3 ha^{-1}. In the most conservative scenario, the average minimum amount of water stored in the peatland equaled 69 m^3 ha^{-1}. Further description of the results refers only to the scenario with r = 50 m and p = 0.83, as it was considered to be a representative average scenario.

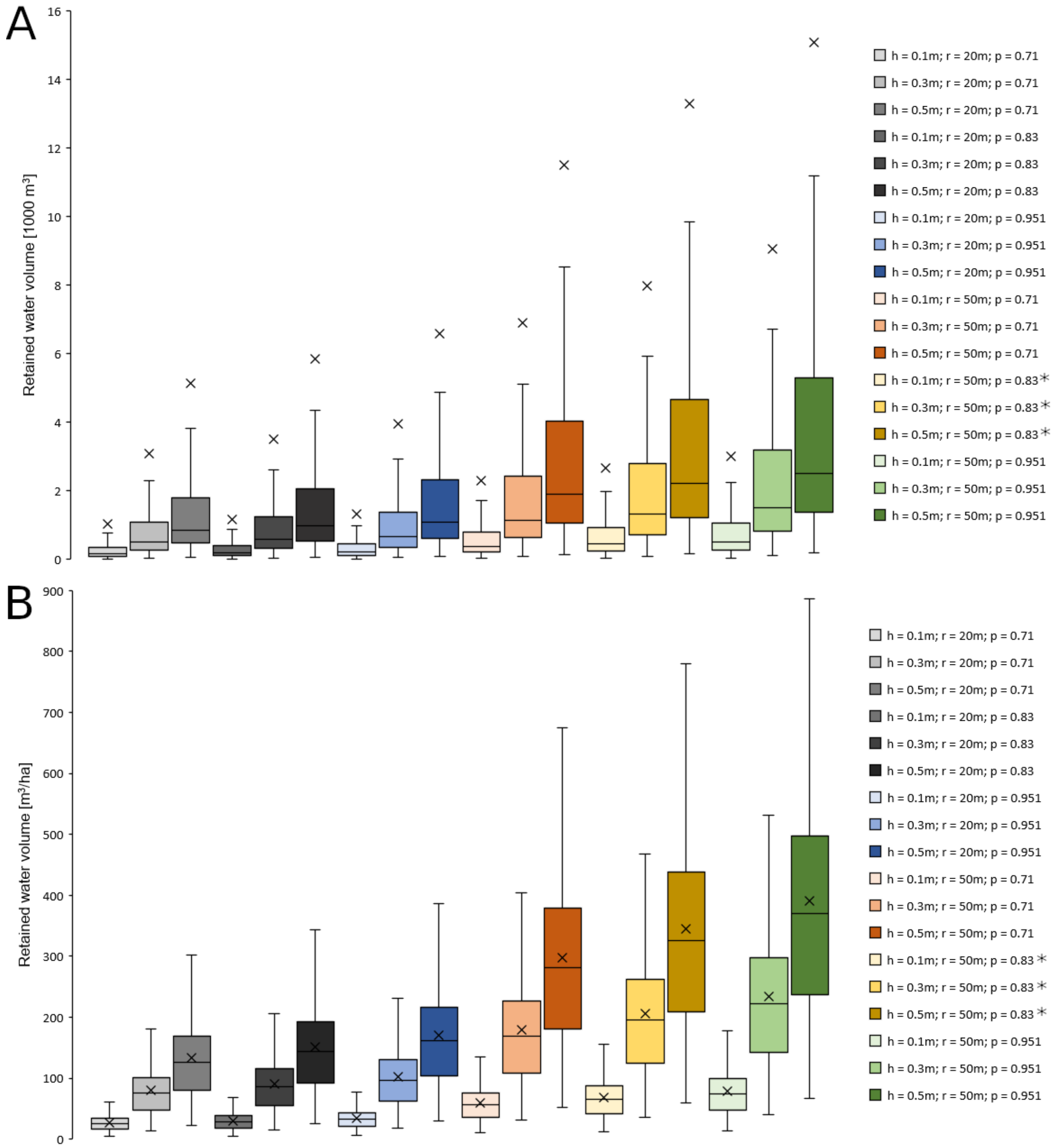

Figure 4. A) Boxplots comparing distributions of a retained water volume per object and B) boxplots comparing retained water volume in $m^3 \cdot ha^{-1}$ in 18 scenarios, using various values of the average radius of water level rise in a cross-sectional view from the ditch, porosity and stacking height. x stands for the average value, box represents the interquartile range of results, horizontal line in the box stands for the median value, whiskers stand for the interval from 5th to 95th percentile, * in the legend indicates the boxplots with representative results, which are later described in the text. Outliers were excluded.

3.2 The value of water retention in a basin-scale

Analysis of available data on the costs of reservoir construction that can be considered in the value of gain associated with water retention at a basin scale showed that the average value of water retention in the Neman Basin was 0.51 EUR $\cdot$ m^{-3} $\cdot$ $year^{-1}$, varying from 0.04 EUR $\cdot$ m^{-3} $\cdot$ $year^{-1}$ in the case of Angiriai Reservoir (Lithuania) up to 1.67 EUR $\cdot$ m^{-3} $\cdot$ $year^{-1}$ in the case of Suwałki Reservoir (Poland;

Tab. 2). The weighted average of reservoir construction costs was 0.097 EUR · m^{-3} · year^{-1}, whereas the arithmetic average value was 0.51 EUR · m^{-3}. It was found that the water retention values did not differ much either between the countries analysed or across periods of reservoir construction (1977-2021). As an obvious consequence of the size and costs of reservoir construction, it was found that the unit value of water retention was much higher in small reservoirs than in the larger ones (Tab. 2).

Table 2. Sample of reservoir construction costs within Belarus, Lithuania and Poland used to assess the average annual water storage value. EUR stands for Euro; RUB stands for Rubles.

Country	**Name of the reservoir**	**Year of construction**	**Coord. GPS X [ºE], Y [ºN]**	**Volume [mln m^{3}]**	**Nominal construction costs**	**Recalculated construction cost [EUR]**	**Water retention value [EUR·m^{3}·year^{-1}]**	**Source**
Poland	Kuźnica - Łosośna	2004	23.6377 53.5053	0.053	1 900,000 PLN	591.487	0.28	Siemieniuk et al., 2015
Poland	Suwałki	2021	22.9255 54.0775	0.004	1 200,000 PLN	267,920	1.67	Guibourgé - Czetwertyński, 2020
Lithuania	Angiriai	1980	23.7435, 55.2818	15.5	1 423,600 RUB	25,317,382	0.04	Anon. 1982
Lithuania	Vaitiekūnai	1980	23.6525, 55.4903	0.5	1 247,220 RUB	22,163,603	1.11	Anon. 1982
Lithuania	Krekenavos	1978	24.0974, 55.5495	0.34	106,780 RUB	1,899,432	0.14	Anon. 1982
Lithuania	Balsupiai	1977	22.5800, 56.0943	0.848	165,000 RUB	2,938,149	0.09	Anon. 1982
Belarus	Остров (Ostrov)	1997	25.9736, 52.9101	2.12	1 818,080 RUB	22,004,527	0.26	https://feeder.by/
						ARITHMETIC AVERAGE	**0.510**	
						WEIGHTED AVERAGE	**0.097**	

3.3 Costs of rewetting

Analysis of available data on the costs of peatland rewetting (Tab. 3) revealed high variability of costs for individual actions. This is because there is no coherent rewetting protocol, and every measure is different from the others due to some specific site features.

Table 3. Estimated peatland rewetting costs based on available data from public procurement procedures of peatland rewetting.

Country	**Location (type of peatland)**	**Year of action**	**Type of action**	**Total cost of one action [EUR]**
Poland	Słowiński NP (bog)	2021	Blocking of a small ditch (+/- 2.0 m) with bags filled with peat and strengthened by wood	90
Poland	Słowiński NP (bog)	2021	Wood-peat block of a small ditch (+/- 2.0 m)	400

Poland	Słowiński NP (bog)	2021	Wooden sheet pile	1500
Poland	Słowiński NP (bog)	2019	Wood-peat block + double sheet pile of a small ditch (+/- 2.0 m)	1200
Poland	Słowiński NP (bog)	2019	Wood-peat block + double sheet pile of a small ditch (+/- 2.0 m)	1150
Poland	Słowiński NP (bog)	2019	Damming spillway of a ditch	900
Poland	Słowińskie Błota (bog/fen)	2017	Damming large ditches (+/- 5.0 m wide) with various types of blocks (averaged value)	1500
Poland	Bagno Kusowo (bog)	2017	Solid wood-peat ditch blocks	1850
Lithuania	Aukštumala Peatland (bog)	2016	Damming drainage ditches 1) peat dams (1.0-1.5 m), 2) plastic dams (1.0-2.0 m wide, 2 m deep) 3) composite dams with water outflow pipe (mixed peat-plastic, geotextile, water tube, elbow for water level regulation, timber logs; 10 m long, 5 wide)	1) 50 2) 80 3) 3000
Lithuania	Sachara Peatland (bog)	2020	Damming drainage ditches 1) peat dams (1,0-2,0 m) 2) plastic dams (4-10 m wide, 3 m deep)	1) 150 2) 1580
Lithuania	Žuvintas Biosphere Reserve (fen)	2021	Damming hand-dug ditches (2 m wide). 1 Dam with culvert (metal pipe) and water level regulation by pulling metal plates 5 m length, 3 m wide	3630
Belarus	Dziki Nikar (fen)	unknown	Damming drainage ditches with peat dams	300
Belarus	Dzikoje (fen)	unknown	Damming drainage ditches with peat dams	430
Belarus	Solomenka (fen)	unknown	Damming drainage ditches with peat dams and wooden dams	1120
			AVERAGE	**1114**

The cheapest individual actions were related to construction of ditch blocks with bags filled with peat and strengthened by wood in small ditches, which was approximately 90 EUR/action. Small peat dams in minor ditches were valued as low as 50 EUR/action. Wood-peat ditch blocks were valued approximately two orders of magnitude higher (namely 1500-1850 EUR/action). Equipping ditch blocks with flow regulation facilities doubles their development costs to approximately 3000-3680 EUR/action; Tab. 3). The average cost of one individual action in peatland rewetting projects (construction of one average ditch block of ‘average’ type in ‘average’ drainage ditch) was 1114 EUR.

3.4 Value of water retention in rewetted peatlands of the Neman Basin

Knowing the total volumes of water stored in rewetted peatlands, the values obtained with $r = 50$ m and $p = 0.83$ scenario were multiplied by the average value of water retention (0.51 EUR $\cdot$ m^{-3} $\cdot$ $year^{-1}$). The total value of retained water due to the damming of ditches was 12 M EUR $\cdot$ $year^{-1}$ when the stacking height equals 0.1 meter, 36.1 M EUR $\cdot$ $year^{-1}$ when the stacking height equals 0.3 meter and 60.2 M EUR $\cdot$ $year^{-1}$ when the stacking height equals 0.5 meter. The minimum estimated cost of restoration of drained peatlands in the Neman River Basin was 6.8 M EUR · year^{-1}, the average was 30.3 M EUR · year^{-1} and the maximum was 51.5 M EUR · year^{-1}, depending on the applied damming scenario (Tab. 4).

Table 4. Estimated costs of technical actions aimed at rewetting peatlands and water retention values (when r = 50 m and p = 0.83).

Calculated values		Belarus	Lithuania	Poland	Russia (Kaliningrad Oblast)	Total
Cost of dams – scenario A [EUR · year^{-1}]		4 156 613	2 529 851	109 287	49 725	6 845 477
Cost of dams – scenario B [EUR · year^{-1}]		18 395 821	11 196 301	483 670	220 068	30 295 861
Cost of dams – scenario C [EUR · year^{-1}]		31 286 939	19 042 259	822 608	374 284	51 526 091
Total retained water volume [m^3]	0.1	16 153 631	6 913 182	324 286	203 665	23 594 763
	0.3	48 460 892	20 739 546	972 857	610 994	70 784 289
	0.5	80 768 154	34 565 910	1 621 429	1 018 323	117 973 815
Total water retention value [EUR · year^{-1}]	0.1	8 238 352	3 525 723	165 386	103 869	12 033 329
	0.3	24 715 055	10 577 168	496 157	311 607	36 099 987
	0.5	41 191 758	17 628 614	826 929	519 345	60 166 646
Net water retention value – scenario A [EUR · year^{-1}]	0.1	4 081 720	1 030 432	58 426	54 148	5 224 726
	0.3	20 558 423	8 081 877	389 198	261 886	29 291 384
	0.5	37 035 127	15 133 323	719 969	469 624	53 358 043
Net water retention value – scenario B [EUR · year^{-1}]	0.1	-10 157 553	-7 517 626	-307 983	-116 178	-18 099 340
	0.3	6 319 151	-466 181	22 789	91 560	5 967 318
	0.5	22 795 854	6 585 265	353 560	299 297	30 033 977
Net water retention value – scenario C [EUR · year^{-1}]	0.1	-23 048 728	-15 256 401	-639 702	-270 379	-39 215 210
	0.3	-6 572 025	-8 204 955	-308 931	-62 642	-15 148 552
	0.5	9 904 678	-1 153 509	21 841	145 096	8 918 106

After deduction of restoration costs, the net value of retained water due to blocking the ditches using the minimum restoration costs scenario was approximately 5.2 M EUR · year^{-1}, 29.3 M EUR · year^{-1} and 53.4 M EUR · year^{-1}, respectively for 0.1-, 0.3- and 0.5-meter stacking height values. With the average restoration costs scenario and the stacking height equaled 0.1 meter, the cost exceeded the total value of retained water and the net water retention value was negative (-18.1 M EUR · year^{-1}). When the stacking height equaled 0.3 and 0.5 meter, the net water retention values were positive in total and equaled 6 M EUR · year^{-1} and 30 M EUR · year^{-1}, respectively. Within the maximum restoration costs scenario, the costs of restoration exceeded the value of retained water when the stacking height equaled 0.1 and 0.3 meter, giving negative values of net water retention (-39.2 and -15.1 M EUR · year^{-1}). The net water retention value was positive and equaled 8.9 M EUR · year^{-1} applying the 0.5-meter stacking height.

Among the countries of the Neman Basin, the highest costs associated with the rewetting activities were revealed for Belarus. The minimum (scenario A) estimated annual-weighted cost of technical actions aimed at rewetting peatlands in this country was approximately 4.2 M EUR · year^{-1}, the average (scenario B) was 18.4 M EUR · year^{-1} and the maximum (scenario C) was 31.3 M EUR · year^{-1}. The total cost of technical actions associated with the rewetting of peatlands in Belarus (calculated as the value in EUR · year^{-1} multiplied by the assumed amortization rate to the power of $^{-1}$ that expressed the number of years for which the installation was designed to function) was approximately 168 M EUR in scenario A, 736 M EUR in scenario B and 1 252 M EUR in scenario C.

The minimum estimated annual-weighted cost of technical actions aimed at rewetting peatlands in Lithuania was approximately 2.5 M EUR · year^{-1}, the average (scenario B) was 11.2 M EUR · year^{-1} and the maximum (scenario C) was 19 M EUR · year^{-1}. The total cost of technical actions associated with the rewetting of peatlands in Lithuania (calculated as the value in EUR · year^{-1} multiplied by the assumed amortization rate to the power of $^{-1}$ that expressed the number of years for which the installation was designed to function) was approximately 100 M EUR in scenario A, 448 M EUR in scenario B and 760 M EUR in scenario C. In Poland, the minimum calculated annual-weighted cost of technical actions aimed at rewetting peatlands was approximately 0.1 M EUR · year^{-1}, the average (scenario B) was 0.5 M EUR · year^{-1} and the maximum (scenario C) was 0.8 M EUR · year^{-1}. The total cost of technical actions associated with the rewetting of peatlands in Poland (calculated as the value in EUR · year^{-1} multiplied by the assumed amortization rate to the power of $^{-1}$ that expressed the number of years for which the installation was designed to function) was approximately 4 M EUR in scenario A, 20 M EUR in scenario B and 32 M EUR in scenario C. In the Kaliningrad Region of the Russian Federation, the minimum annual cost of technical actions of peatland rewetting reached approximately 0.05 M EUR · year^{-1}, the average 0.2 M EUR · year^{-1} and the maximum 0.4 M EUR · year^{-1}. The total cost of technical actions associated with the rewetting of peatlands in this region was approximately 2 M EUR in scenario A, 8 M EUR in scenario B and 16 M EUR in scenario C (Tab. 4).

4. Discussion

4.1. Peatland rewetting as an optimal solution for increasing water retention in the landscape

The analysis of average values of water retention in rewetted peatlands in the Neman Basin (from 23.6 up to 118 M m^3) provides important information that is currently not available. Comparing the water retention to artificial reservoirs constructed in the Neman Basin (e.g., Bilys et al., 2017), to the rewetting of peatlands offers a similar, great potential for increasing water retention at the basin scale. Moreover, turning water storage from artificial reservoirs to spatially distributed rewetted peatlands placed predominantly in an agricultural landscape remains a valuable management tool. This would improve water retention throughout the landscape that will soon require water resources to be increased due to changes in climate and increased risks of droughts, which will pose the greatest challenges to the agriculture sector of the region's (Stonevičius et al., 2017). Indeed, peatlands affect the flow regime of the river, but drainage is slow and limited, and reduction of runoff and flow to the Neman River after rewetting of drained peatlands would be temporary (Kharanzhevskaya et al., 2020). As studies have proven that the efficiency of reservoirs in reducing warm season runoff in the Neman basin is low (0.3-1.2%), even for large reservoirs (of several hundred hectares) (Rimkus et al., 2013), one can argue if their construction is the answer for keeping water in the landscape. This issue is significant given that the reasons for the lack of water in the landscape over recent years has been caused by meteorological phenomena and the real driving forces of water shortages are the feedback of human actions (like river regulation and construction of the reservoirs that evaporate vast shares of inflowing water) and the climate (Savelli et al., 2021). Therefore, this study shows the rewetting of peatlands might do a better job in increasing water retention and slowing down the water cycle. In parallel, observations on the development of the EU Common Agricultural Policy strategies (e.g., European Commission, 2020), indicate that increasing carbon stock in soils is a key priority that is gradually taking over other priority goals of maintaining agricultural environments. Thus, the rewetting of peatlands toward restoring carbon sequestration processes to sites that have been drained previously may appear as an integrated approach to the successful and nature-based adaptation of agriculture towards meeting the modern challenges in managing social-ecological systems, although this type of evaluation was not included in this analysis.

4.2. Monetary valuation of water retention

The value of water retention calculated in the approach applied in this study allowed to estimate the annual value of water retention in rewetted peatlands. The final, arithmetic average, multi-annual unit value of water retention in the Neman River basin that equalled 0.51 EUR $\cdot$ m^{-3} $\cdot$ $year^{-1}$ allowed to compare the value that society gains from the investment in technical rewetting of peatlands. In the study of Grygoruk et al. (2013), the unit value of water storage calculated on the basis of different datasets and in a different river basin, was very similar and equaled 0.53 EUR $\cdot$ m^{-3} $\cdot$ $year^{-1}$. Although these similar values clearly remain a coincidence and result from a random and unbiased selection of different reservoirs analysed in both cases, one could hypothesize that the unit value of water retention did not differ much between the neighbouring basins and across years. It can be considered an interesting observation valuable for other studies in the future that deal with valuing water retention as an ecosystem service, especially in the context of wetlands. It is essential to keep in mind that the value of water retention calculated this way may not represent the overall real value of stored water, as reservoirs, on top of storing water, offer other benefits and risks. Nonetheless, the results of this analysis can be considered a first step in discussion on monetizing the role of rewetted peatlands in the landscape. When having other estimates of the unit monetary value of water (e.g., calculated using other economic approaches) one could improve the level of detail in similar assessment and provide better quantification. At this step, however, it was found that there is no reason to reject the applied methodology given the urgent need for developing algorithms capable to quantify monetary benefits of environmental restoration and wise environmental management (BenDor et al., 2015).

4.3. Optimal rewetting case

Results from this study indicate, that the possible gains in water storage capacity due to the blocking of ditches located in the peatlands area with dams differs significantly, depending on the applied stacking height and types of actions applied in rewetting. The highest increase in water retention was observed when the stacking height equals 0.5 meter. However, the most suitable damming height should be chosen individually for each peatland, based on the initial groundwater table and peat depth (Similä et al., 2014). Peat subsidence after the drainage along with a multiple dredging of ditches in history have changed every drained mire in terms of the bulk density of soils, elevations and geochemistry (Liu et al., 2020; Hohner and Dreschel, 2015). Thus, ditch blocking should be done in an adaptive manner to avoid any undesirable effects e.g., flooding of fens. Bearing these limitations in mind, the results indicate that only the highest stacking (damming) heights (0.3 and 0.5 m) applied resulted in a positive economic balance when it comes to comparing the cost of rewetting and the value of water retained in the rewetted peatlands (Tab. 4). In scenario A, every combination of dams and stacking heights provides a positive economic balance – rewetting is always a gain, when one assumes that all ditches are small and do not require extensive investments in damming. This assumption, however, is seldom fulfilled and the rewetted systems consist of sets small and larger ditches. In scenario B, although the damming applied provided the increase of water levels, it does not compensate in economic terms the costs of ditch blocking, especially in the lowest damming assumptions. In scenario C, only the highest stacking heights provide a positive economic balance. Contradictory to scenario A however, in this approach it was assumed that the ditches are large and rewetting itself remains a costly investment. This assumption, similar to scenario A, is also seldom fulfilled in reality because of the same reasons: drainage networks consist of a variety of ditch sizes, in terms of depth and width. From this estimation, one can conclude that decision making on the rewetting of drained peatlands done as a background for increasing water retention should be oriented at constructing the highest-possible ditch blocks, which do not cause excessive flooding of peatlands and would help to avoid negative consequences, such as internal eutrophication. Such an approach may help the standard approaches of ditch blocking to become more efficient and optimal (Grand-Clement et al., 2015).

4.4. Risk of excessive evapotranspiration

Increased availability of water in the rewetted peatland might indeed induce the increase of evapotranspiration by phreatophytic plants. However, this process is expected to be a feedback. Increasing saturation of the soil in drained peatland prevents trees and shrubs expansion (e.g., Scharnweber et al., 2015), which have much stronger ET potential (stomatal transpiration) than the species of sedges, grass and cattail that usually appear in the rewetted peatland. Hence, although the availability of water in the root zone is expected to increase in result of rewetting, the consumption of water by phreatophytes is expected not to change significantly, as high water levels prevent forest expansion and the diurnal patterns of groundwater consumption by grass-type vegetation does not affect water balance of the habitat (Grygoruk et al., 2014). However, the process of changing ET due to rewetting should be examined in more detail, preferably with in model-based approaches capable to simulate vegetation-groundwater level feedback.

4.5. What can be gained through peatland rewetting?

Evaluation of possible water retention gain with the highest damming height scenario (0.5 meter) revealed that the potential economic benefit from retained water due to rewetting drained peatlands in the Neman River Basin exceeds the costs of rewetting by approximately 10 M EUR per annum. The foreseen expenses of rewetting depend on the sizes of peatlands and the share of a country's area in the total area of the Neman River basin. Thus, the highest expenses related to the construction of dams can be expected on the Belarusian side (4-31 M EUR $\cdot$ year^{-1}) and the lowest – in the Kaliningrad Region of the Russian Federation (approximately 0.05-0.4 M EUR $\cdot$ year^{-1}). At the same time, the highest benefit from rewetting is expected in Belarus. However, in Lithuania, the results of scenario C for the value of water retention in rewetted peatland unexpectedly did not exceed the cost of rewetting (overall balance in the scenario C equaled -1.2 M EUR $\cdot$ year^{-1}).

These results do not indicate that peatland rewetting is economically inefficient, but rather indicate that in Lithuania (as well as in the other countries analyzed) peatland rewetting should be optimized to secure the most important peatland and help reduce its costs. Indeed Manton et al., (2021), applied spatial planning of the Peatlands of the Neman River Basin and showed that peatland fens in agricultural landscapes require the highest levels of restoration and that restoration needs to target specific areas. As it was indicated in the analysis of costs of actions (Tab. 3), sophisticated ditch blocks equipped with water level regulation facilities increase the rewetting cost by approximately 400% when compared to simple ditch blocks made of wood and peat.

Additionally, other factors should also be considered, for instance the analysis in this study addressed – on one hand – the valuation of only one ecosystem service, which is water retention. Whereas, peatland restoration by rewetting can deliver a range of other ecosystem services (such as, carbon storage, biodiversity conservation, nutrient retention or cultural services; Maltby, 2009; Okruszko et al., 2011); however, there is often a risk that restoration of peatland hydrology may trigger negative phenomena such as secondary eutrophication of the ecosystem (Banaszuk et al., 2011). Such a comparison, preferably at the level of one river basin, may indicate the real role of peatland rewetting in economic gains obtained from this initial restoration actions. For instance, Jenkins et al. (2010) diagnosed that the social value of restored wetlands surpassed the public expenditure on wetlands restoration due to gained value of ecosystem services in only 1 year. On the other hand, on the side of rewetting costs in this study the costs of planning of rewetting activities or any disservices were not included. For example, a farmer may encounter a loss of farming land, e.g., land purchase, loss in cropping area. Despite this, this research can be viewed as the first step towards understanding the benefits of peatland rewetting at a large river basin scale. To reduce the uncertainty of the results, it is necessary to conduct more similar analyses in different river basins. The complexity of basin landscape analysis delivers a broad estimate of the benefits and gains expected. Therefore, it is recommendable to undertake analysis targeting smaller localized sub river basins for restoration, where the monetary costs and benefits of rewetting from re-established ecosystem services can be quantified more accurately. The methodology applied in this study provides an opportunity to do this.

4.6. Adopted assumptions and the issue of asymmetric distributions

In the analysis it was also assumed that the minimum size of peatlands for rewetting (drained peatlands) to be 5 ha (excluding Belarus, where all of the available data was used due to the inaccessibility of better-quality data sources (see Manton et al., 2021 for detailed discussion on the data limitations). This assumption could result in removing fragmented or small peatland areas that form a peatland complex. The development of the natural landscape of the Neman River basin was split between two periods. Firstly, the last deglaciation of the Vistulian (Late Neman) ice sheet resulting in numerous scattered depressions that have formed many small-sized peatlands in Lithuania (Guobytė 2004). Secondly, the Saalian age, with a monotonous ‘mature’ old morainic landscape that contain bottom moraines, fluvioglacial plains and lowlands that favored the formation of large peatland in Belarus (Karácsonyi 2017). Thus, changing the minimum patch size selection would increase the availability of peatland for restoration and the expected benefits of water retention for Lithuania. Therefore, altering the approach used in this study to include all peatlands would have changed the final results. However, this fact is not expected to change the final balance of the results. A full list of assumptions used in the study was provided in the Supplementary material.

Asymmetric distributions of results represent the issue of scale. In the headwater parts of the Neman River Basin, several vast peatlands strongly influence mean values, while the distributions are skewed toward smaller peatlands. This explains why the median values of total volumes of water retention are several times lower than the mean values. This also indicates that the restoration of large drained peatlands would allow for the highest gain in water retention at the basin scale, but at the same time they would also be the most expensive to restore.

4.7. Sustainable peatland management

This study shows a best-case scenario for the restoration of all drained peatlands > 5 ha through rewetting. However, it is highly unlikely that all degraded peatlands can be restored. For instance, landowners may not be willing to change the farming practices. Therefore, strategic spatial planning is needed to help plan and prioritize the conservation and restoration of peatlands (Manton et al., 2021). A recent study on the conservation and restoration opportunities in the Neman River Basin showed that the quality of peatlands under protection is inadequate (Manton et al., 2021). Thus, peatland restoration is required of which rewetting is the first step. Combining the study of Manton et al., (2021) with the results of this study should be explored further as it can provide a path towards better spatial planning that include robust a cost benefit analysis for rewetting.

Currently, wetland restoration is a subject of many doubts and concerns in the scientific community. In light of the progressive wetland degradation and climate change, researchers reflect upon the cost-effectiveness of rewetting measures and the impact they have on recovering wetland functions. Proposed actions oriented at rewetting of drained peatlands in the Neman River Basin have great potential and should be considered as spatial and landscape-scale adaptation measures that sustain water resources at a local scale. Similar to Savelli et al. (2021) it was hypothesized, that observing changing water resources (Stonevičius et al., 2017) and attributing their shortages in a country-wide or a river basin-wide perspective only to climatic drivers, one could not successfully adapt to foresee climate impacts on agriculture. Rewetting of peatlands at the basin-scale allows for distributing and stabilizing water resources in space. This action reduces the risks of droughts and promotes the development of resilient and diverse ecosystems which – together – entails the development of a resilient lowland environments managed for agriculture.

5. Conclusions

Rewetting drained peatlands remains a complex, but efficient restoration tool that aims towards increasing river basin scale water retention. In this study of the transboundary Neman River basin, it was revealed that rewetting can be considered an effective management tool capable to increase the water storage of its basin by nearly 1% of the total annual runoff. Costs associated with necessary works oriented at the construction of various types of ditch blocks (damming facilities) are – in general - lower than benefits associated with the monetary value of water storage. Results of this study indicate that the highest gain from rewetting in terms of the value of water storage occurs when land reclamation systems subjected to blocking the outflow are equipped with the highest possible dams (of different type), without causing excessive flooding of the rewetted systems, to avoid secondary eutrophication, and constructed dams are not equipped with any water-level-regulation facilities. The methods developed and applied in this study can also be used at multiple scales to help understand the values of rewetting-based restoration. Finally, the economic benefits from rewetting are expected to be even higher than the ones presented in this study, as only one ecosystem service related to water retention was addressed.

The results obtained in this study deliver an important perspective for the most up to date strategies drafted for the development of common agricultural policy of the European Union. Firstly, the proposed measures can synergically increase the safety of agricultural water resources against droughts. Secondly, presented actions promote increased water retention through relatively inexpensive installations scattered across the agricultural landscapes of lowlands. Thirdly, proposed actions positively influence the content of carbon in soils – which slowly dominates the paradigms of modern sustainable agriculture of the EU member states. Fourthly, rewetting enhances the quality of the environment by re-establishing biodiversity niches in a restored agricultural landscape. Finally, the conclusions presented in this research may allow individual users and policy makers to develop, establish and apply financial mechanisms that promote sustainable water management in agricultural landscapes that depend on the volumes of water stored in rewetted organic soils. This would assure (or – at least – initialize) the restoration of degraded peatland environments and allow users to benefit from maintaining high quality peatland environments, so the historical scale of degradation of peatlands for agriculture, known in Europe from a fresh historical perspective, is assured never to happen again.

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