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SURFACE WATER STORAGE IN THE ORAVA – NOWY TARG BASIN, WESTERN CARPATHIANS

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Abstract

The Orava – Nowy Targ Basin is one of 31 basins found in the Western Carpathians. While average in size (643 km^2), it is the only basin where large amounts of water are stored in vast peat bogs. Until the 16th century, it had not been inhabited and the amount of water stored in peat at that time was estimated to be 171 million m^3. Due to the anthropogenic degradation of peat bogs the amount of water has decreased 2.7 times and it is now estimated at 62 million m^3. Two dams built in the basin, in the second half of the 20th century, retain reservoirs that store 563 million m^3 of water. This amount of water exceeds the earlier loss of water in peat five times over. If the planned, more ambitious project of dam construction in the basin had been completed, the total capacity of the reservoirs would exceed the water loss in peat by 27 times. The index of lake retention including peat in relation to the area of the basin is determined to be currently 98 cm, but if the project of maximum development of the reservoirs in the basin had taken place, it would reach 270 cm. The estimated useful lifetime of the reservoirs studied suggests theoretically an 80% loss of their initial capacity over a timescale of one thousand years. Taking into account the current regeneration of peat bogs, there is an optimistic outlook for the protection of the natural and anthropogenic water resources of the basin.

Key words

surface waters • peat bog • dam-retained reservoir • Orava – Nowy Targ Basin • Orava – Podhale Peatland • Carpathians

Introduction

Inner-mountain basins, especially those which are adjacent to high mountains, show large but annually changeable resources of surface water (Lwowicz 1978; *Hydrogeography*... 1983). Only certain areas in these basins may permanently store large amounts of water in the form of natural lakes, artificial reservoirs and swamps. The storage of large amounts of water also takes place in layers of peat in the domes of vast raised bogs, in fens and also in peat soil and half-bog soil used as meadows (Gilman 1994; Price 1997;

Price & Schlotzhauer 1999; Charman 2002; Brandyk et al. 2006; Łajczak 2013).

The aim of the paper is evaluation of surface water storage, including storage in peat deposits, in the Orava – Nowy Targ Basin in the Western Carpathians. Attention was also paid to the changes in water storage in peat deposits influenced by human activity over the last ca. 500 years. The volume of current water storage in reservoirs retained behind dams was shown as well as the hypothetical situation in which planned dams had been built in the basin. The volume of surface water storage in the basin was related to the volume of river discharge with special reference to groundwater discharge.

While choosing the Orava – Nowy Targ Basin as an area for investigation, the unique hydrographic features of this area were taken into account. The Orava – Nowy Targ Basin is one of 31 basins in the Western Carpathians (Starkel 1972; Kondracki 1989) (Fig. 1). However, it is one of the few basins in the Carpathians which is almost totally covered by vast fluvioglacial fans rich in groundwater (Ziemońska 1973; Chowaniec 2009). The hydrogeological conditions of this basin produced an array of vast peat bogs, especially raised bogs, unique in the whole Carpathians (Łajczak 2007). In the Orava – Nowy Targ Basin, as in other Carpathian basins, there are no natural lakes. However, there are two large dam-retained reservoirs in the area studied. In the past there were plans to construct several more reservoirs, but they have never been implemented. The evaluation of anthropogenic changes in the amount of water retention in peat in the basin is based on the well documented history of human activity in this area.

Study site

The Orava – Nowy Targ Basin developed at the border of the Central Western Carpathians and the External Western Carpathians (Cieszkowski et al. 2017) and is located north of the Tatras (2,655 m a.s.l.). The Beskidy Mountains are located north of the basin. They are built

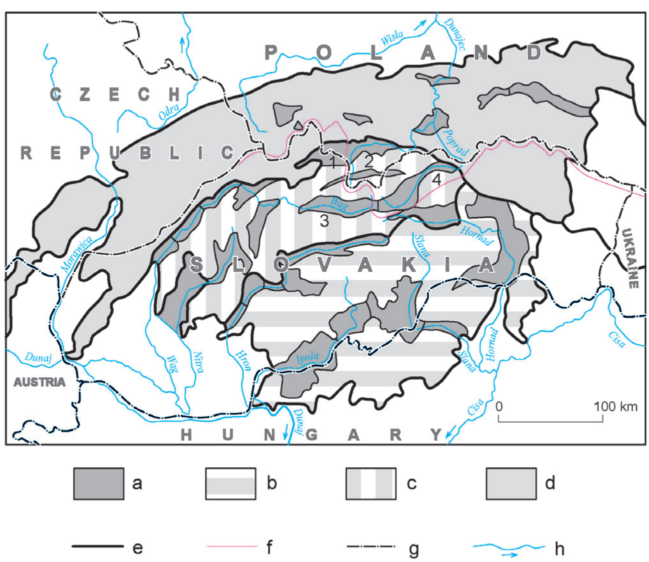

Figure 1. Location of the Orava – Nowy Targ Basin within the Western Carpathians against the background of other basins (according to Starkel 1972; Kondracki 1989). a – extent of the basins (1 – Orava – Nowy Targ Basin, 2 – Podtatrze Foredeep, 3 – Liptov Basin, 4 – Poprad Basin), b – Inner Western Carpathians, c – Central Western Carpathians, d – External Western Carpathians, e - limit of Carpathians and border among Inner Western Carpathians and Central Western Carpathians and External Western Carpathians, f – continental watershed, g – state boundaries, h – main rivers

of Magura flysch sediments and represent medium-mountain relief. Most of the area located between the Tatras and the basin are high foothills built of Podhale flysch (Fig. 2A). The basin covers an area of 643 km^2 and its altitude range is between 487 and 800 m a.s.l. It is the fourth highest located basin in the Western Carpathians just after the Podtatrze Foredeep, Liptov Basin and Poprad Basin (Fig. 1). The basin is crossed by the continental watershed which here runs in a N-S direction and divides the drainage area of the Black Sea (55% of the basin area) from drainage area of the Baltic Sea (45%) (Figs. 1 & 2B). The basin is also divided by the Polish-Slovak border and 67% of its area lies in Poland.

The Orava – Nowy Targ Basin is of tectonic origin and is filled with lacustrine sediments of Neogene age covered by Quaternary gravels overlain by a 200 cm thick layer of clay (Cieszkowski et al. 2017). The fluvioglacial gravel fans of three rivers (Czarny Dunajec, Biały Dunajec, Białka) cover almost the entire floor of the basin (Fig. 2B). On the surface of these fans, terrace levels and, locally, paleochannels developed. Discharge of shallow groundwater occurs within concave forms. Water-bearing gravels are drained through poorly permeable clay (Łajczak 2013), and stable outflows of these waters enable hydrogenic habitats to develop and be transformed into fens and then into raised bogs. Apart from hydrogeological and geomorphological factors, the development of peat bogs is also conditioned by a cool and humid climate (mean annual precipitation: 850-1,000 mm, Kożuchowski 2017).

Figure 3A shows the limits of the sections of the Orava – Nowy Targ Basin where peat bogs are located. The probable limit of peat bogs within the basin before ca. 1500 is shown in Figure 3B. Currently habitats of hydrophilous vegetation excluding peat cover 3% of the area of the basin, whereas fen, residual domes of raised bogs and post-peat areas with a preserved thin layer of peat cover 9% of the basin area (Fig. 3C). The peat bogs in the basin belong to the topogenous or soligenous types, and a few to the ombrogenous type. The peat bogs occur at an altitude from 592 to 770 m a.s.l. (Łajczak 2007). Since the 16th century the peat bogs in this basin have been

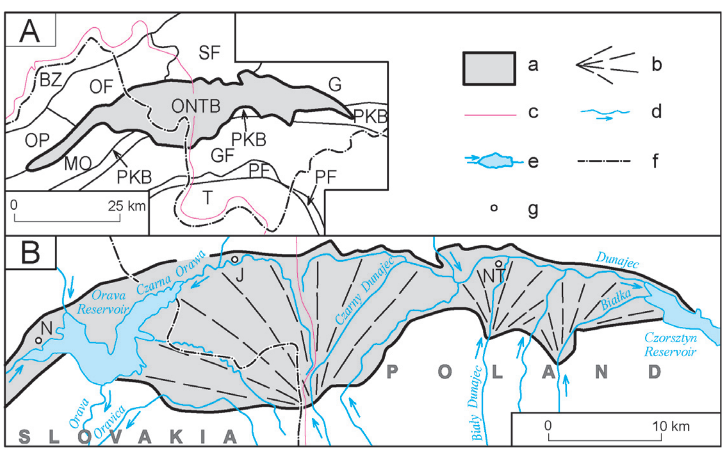

Figure 2. The Orava – Nowy Targ Basin against the background of the adjacent geomorphological units (according to Starkel 1972; *Geomorfologicke členienie...* 1986). A. ONTB – Orava – Nowy Targ Basin, BZ – Beskid Żywiecki Mountains (Oravské Beskydy in Slovakia), G – Gorce Mountains, GF – Gubałówka Foothills, MO – Magura Oravska Mountains (Oravska Magura), OF – Orava Foothills (Podbeskydská Vrchovina), OP – Orava Plateau (Oravska Vrchovina), PF – Podtatrze Foredeep, PKB – Pieniny Klippen Belt, SF – Sieniawa Foothills, T – Tatra Mountains; B. Extent of fluvioglacial fans in the basin: J – Jabłonka, N – Namestovo, NT – Nowy Targ. a – basin boundary, b – fluvioglacial fans, c – continental watershed, d – main rivers, e – dams and reservoirs, f – state boundary, g – main towns

degraded by human impact – at first they were burnt-out and then, at the turn of the 19th and 20th centuries, their limit and thickness were considerably reduced due to peat exploitation and drainage by a dense network of ditches (Łajczak 2007, 2013). After 1990, as a result of decreasing peat exploitation for local heating and balneological purposes, shrinkage of the boundaries of peat bog domes slowed down or even stopped. Most of drainage ditches in the post-peat areas and in the areas adjacent to peat bogs are not cleared which causes the development of vegetation and progressing waterlogging of post-peat areas.

Two large dam-retained reservoirs are in operation in the Orava – Nowy Targ Basin. In 1953, the Orava Reservoir (Vodná nádrž Orava) was opened in the western, Slovak part of the basin. In 1997, in the eastern, Polish part of the basin, the Czorsztyn Reservoir was commissioned (Fig. 4). The capacity of the Orava Reservoir at its highest water stage is 331 million m^3, and Czorsztyn Reservoir – 232 million m^3 (Banach 1992; Łajczak 2017a). In the 1970s there were plans to build more dams in this area – on the Czarny Dunajec, Biały Dunajec, and Białka rivers. According to the project the capacity of the Czarny Dunajec Reservoir was going to be 100 million m^3, whereas the other planned reservoirs were going to be smaller (Kojsówka, Szaflary and Jurgów were going to be located in the areas adjacent to the basin) (Kordas 1982; Gabryś et al. 1986). At the beginning, water retention was going to be higher in the existing reservoirs, so their total capacity was

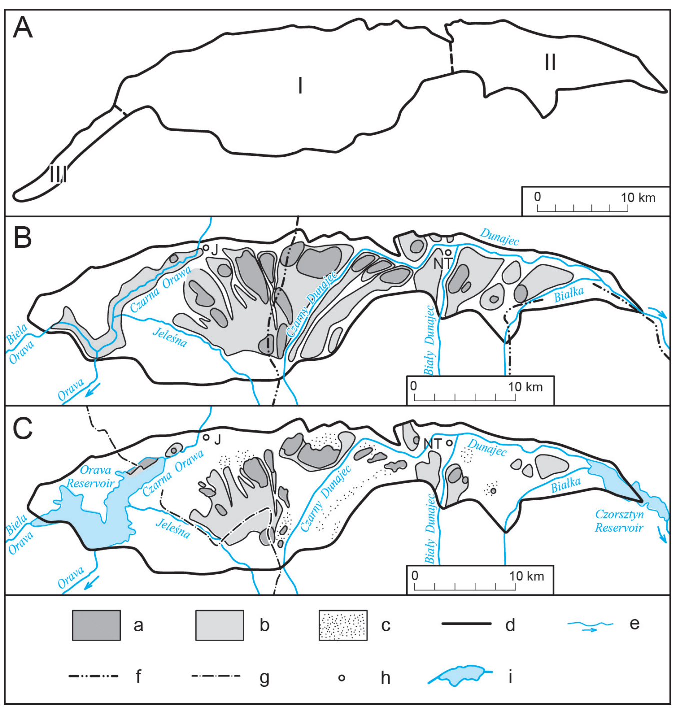

Figure 3. Limit of peat bogs in the Orava – Nowy Targ Basin. A – sections of the basin where peat bogs are located (I – Orava Basin, II – Nowy Targ Basin) and without peat bogs (III – Biela Orava – Hruštinka Depression); B – probable boundary of peat bogs from before 1500; C – contemporary distribution of peat bogs. a – domes of raised bogs (earlier the whole area of the domes, now only residual domes with young post-peat areas), b – fens, c – main areas of hydrophilous vegetation without peat deposits, d – basin boundary, e – main rivers, f – boundary of Poland before 1772 and in the period 1772-1920, g – present boundary of Poland, h – main towns (J – Jabłonka, NT – Nowy Targ), i – reservoirs

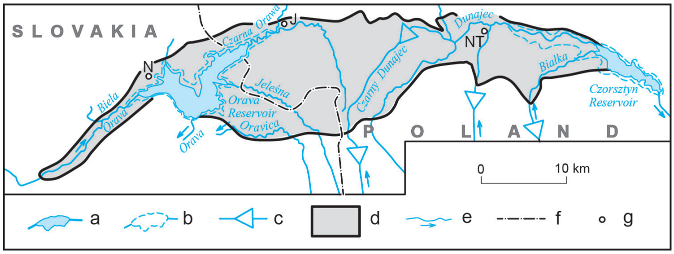

Figure 4. Reservoirs in the Orava – Nowy Targ Basin. a – existing reservoirs, b – maximum limit of water retained behind the existing dams at the planning stage, c – reservoirs proposed in the 1970s and 1980s (their proposed limits are indicated schematically), d – basin boundary, e – main rivers, f – state boundary, g – main towns (J – Jabłonka, N – Namestovo, NT – Nowy Targ)

going to be 2.5 times larger than it is now and would amount to about 1,400 million m^3. In such a situation, taking into account the information included in the literature cited, the Orava – Nowy Targ Basin together with the adjacent areas would make a large reservoir of artificially stored surface water with a capacity of at least 1,700 million m^3, which would be 3 times larger than at present.

There are three fishing ponds in the study area located near Krauszów and Ludźmierz. In the area of a gravel quarry, in the northern part of Czarny Dunajec village, there is a large pit filled with water. Tiny pits filled with water occur within post-peat areas among numerous residual domes.

There are 19 water-gauging stations of the Polish and Slovak Hydrological Services which operate on the rivers in the Orava – Nowy Targ Basin and in its drainage catchment (Fig. 5). Measurement results of three of these stations were analysed in this work.

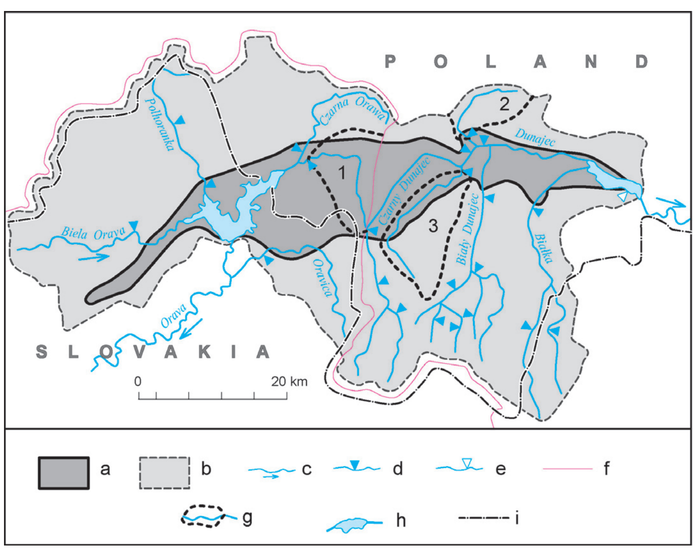

Figure 5. Distribution of water-gauging stations of the Polish and Slovak Hydrological Services on the rivers in the Orava – Nowy Targ Basin. a – basin boundary, b – limit of the basin catchment, c – main rivers, d – water-gauging station on the rivers, e – water-gauging station on the Dunajec river removed after the Czorsztyn Reservoir was built, f – continental watershed, g – boundaries of river catchments studied (1 – Piekielnik Orawski, 2 – Lepietnica, 3 – Wielki Rogoźnik), h – reservoirs, i – state boundary

Materials and methodology

Evaluation of water storage in the Orava – Nowy Targ Basin includes the capacity of the two reservoirs (Orava and Czorsztyn) at maximum water height, and also the capacity of the other reservoirs planned in this area in the past. The current capacity of the existing reservoirs was taken into account indicating the decrease of their capacity together over time with the silting-up of the reservoir basin. The time in which efficient functioning of the reservoirs takes place was estimated – their useful life (Łajczak 1996). Later, due to considerable silting of the basin, reservoirs do not perform their functions and only store a small amount of water.

Side by side with water storage in the reservoirs, current water storage in the vast peat deposits in the basin was analysed. The value obtained was compared with the supposed situation in the past before the anthropogenic degradation of the peat bogs started.

The analysis of water storage in the Orava – Nowy Targ Basin did not include the decrease of water content in the soil, waste-mantle and alluvial deposits as a result of human impact (increased drainage caused by the construction of field roads and deepened channels). This loss of water was difficult to evaluate and it was assumed inconsiderable in relation to the water loss in the widespread peat bogs which are degraded by human impact (Łajczak 2017a). Other water features which were not taken into account due to their negligible incidence in the area include the water in fishing ponds, in the pit in the gravel quarry, and in the tiny pits in areas remaining after peat extraction. Water in the areas covered by habitats of hydrophilous vegetation without a peat layer were also excluded from the investigation.

The total amount of water stored in the basin by reservoirs and peat deposits was assumed to be the predominate form of surface water storage in this area. The quantity of water storage was expressed in cubic metres and in centimetres. Further information in the methodology of the research concerns the calculations of water content in peat, which requires one first to calculate the volume of the peat deposit and then the capacity of peat to store water (Łajczak 2013).

The contemporary boundary of individual peat bogs in the Orava – Nowy Targ Basin, both on the Polish and Slovak sides, was determined based on topographic maps and aerial photographs. Additionally, these boundaries verified based on the results of geomorphological and hydrographic mapping carried out by the author in 2000 with the use of GPS methods. Field investigations were repeated in 2015 using data from aerial laser scanning LiDAR (compare Fig. 3C). In the case of raised bogs, the following elements were determined: boundaries of domes reduced by human activity, boundaries of post-peat areas with a preserved, even thin layer of peat, location of isolated peat patches beyond the present post-peat areas. Based on the criteria for the minimal area of peat bog and deposit thickness within a peat bog (Myślińska 2001), peat patches were assumed in those places where the peat bog area did not exceed 0.5 ha and the deposit thickness is smaller than 20 cm. The boundaries of fens was determined and also water-logged areas with hydrophilous vegetation but without peat cover were identified. The latter represent places for the potential development of peat bogs (Dembek et al. 2000) or indicate the outer limits of peat bogs (especially fens?) before the anthropogenic destruction of large areas covered by peat bogs (Łajczak 2007). The location and dimensions of anthropogenic forms in peat bogs and their neighbourhood were determined, which included exploitation and post-exploitation escarpments, drainage ditches, holes in peat within post-peat areas.

Using drilling methods or an avalanche sounder, the thickness of the peat deposit was measured within each peat bog. These measurements were carried out within squares of a side of 200 m. The network of squares was determined using GPS methods and the squares cover the whole area of individual peat bogs. The measurements were carried out in the period from August to October when the peat bog surface is relatively dry. At that time however, the tops of peat bog domes are seasonally lowered. Therefore, taking into account the process of water storage through peat bog pulsation (Horawski et al. 1979; Szuniewicz et al. 1993; Gilman 1994; Szajda & Olszta 1995; Price 1997; Price & Schlotzhauer 1999; Oleszczuk 2011), the results of peat deposit thickness in all the peat bogs investigated may be assumed as comparable. The thickness of peat deposit obtained in each peat bog is smaller than its maximal value from the period of largest water saturation in spring and represents values assumed as typical from the end of summer and beginning of autumn. In evaluation of the thickness of three peat bogs (Baligówka, Bór za Lasem Kaczmarka, Puścizna Wielka) material obtained from the Peat Works 'Bór za Lasem' in Czarny Dunajec was included. Based on the author's measurements and data obtained from the Peat Works, the contemporary mean thickness of the peat deposit was estimated as well as the volume of peat in individual domes, post-peat areas and lagg-fens.

Based on topographic maps from the years 1779-1782, 1855, 1894, 1902, 1937, 1965 and 1997[1], aerial photographs from 1994 (ca. 1:20,000), and the results of present field mapping, the changes in the boundaries of individual peat bogs (especially peat domes and post-peat areas) during the last 240 years were estimated. On the two oldest maps, only the largest peat bogs are marked, however the others are marked as water-logged areas. These maps contain only the Podhale part of the Orava – Nowy Targ Basin (former Galicia). The outer limits of the peat domes on these maps are delimited by the exploitation escarpment, and the adjacent post-peat areas are marked as places of peat exploitation. The outer limits of peat domes, post-peat areas and fens as well as the course of drainage ditches are marked more and more precisely on the maps from the second half of the 19th century and embrace the whole basin. The limits of peat bogs, especially the domes, before 1780 were reconstructed from traces of peat deposits in places where post-peat areas were not even marked on the succeeding maps. An attempt was made to mark the probable limit of peat bogs before the beginning of peat exploitation (before 1500) taking into account isolated traces of peat deposit, adjacent places with hydrophilous vegetation and ground topography (bearing in mind that each raised bog and its dome is oval-shaped) (Fig. 3B).

In the period before the beginning of anthropogenic degradation of the peat bogs, the average thickness of peat deposit in each dome was assumed to be equal to the contemporary thickness of residual domes, which was calculated for late summer and early autumn. In the case of fens, taking into account the possible total loss of peat deposits of the smallest thickness, it was assumed that the former average thickness of peat deposit was the same as the presently occurring peat deposits of the smallest thickness. Assuming the estimated area of individual peat bogs and probable peat thickness within these peat bogs before the 16th century, a probable volume of peat deposit in raised bogs and fens in the basin at that time was calculated.

In order to determine the amount of water in peat, four raised bogs and four fens were sampled between May and October 2008 (every two months). These were assumed to be representative for the study area. Using Kopecky`s cells (0.25 dm^3), 540 peat samples were taken, which formed the base from which to calculate the capillary capacity of peat by volume (Pwv) in percentages. Peat samples were taken in the following raised bogs (residual domes and adjacent post-peat areas): Puścizna Wielka, Baligówka, Przymiarki and Bór na Czerwonem, and in the following fens: Puścizna pod Pustą Polaną, near Puścizna Rękowiańska, near Bór na Czerwonem, near Otrębowskie Brzegi (Fig. 6). In case

[1] *Karte des Königreiches Galizien und Lodomerien* (F. von Mieg, 1:28,800), *Administrativ-Karte von den Königreichen Galizien und Lodomerien…* (K. Kummerer Ritter von Kummersberg, 1:115,000), *Spezialkarte der k.k. Österreichisch-Ungarischen Monarchie…* (1:75,000), *Geological Atlas of Galicia*, Tactical Map of Poland (Military Institute of Geography, 1:100,000), map of districts (1:25,000), topographic maps (1:10,000).

of the largest raised bog domes (Puścizna Wielka – 356 ha, Baligówka – 203 ha) peat samples were taken from 10 sites along the longer axis of the dome, whereas in residual domes (Przymiarki – 46 ha, Bór na Czerwonem – 31 ha) they were taken from 5 sites. In post-peat areas located around the sample domes, 5 samples distributed regularly along the axis of post-peat areas were taken in each peat bog. In fens, peat samples were taken in 3 sites along the ground fall.

Peat samples in domes of raised bogs were taken at the following depths: in trial pits from the lower limit of acrotelm (50 cm) to a depth of 100 cm, and deeper, using a core drill to a depth 400 cm (every 100 cm). In the domes, peat sampling usually took place at five depths, in post-peat areas at one depth,

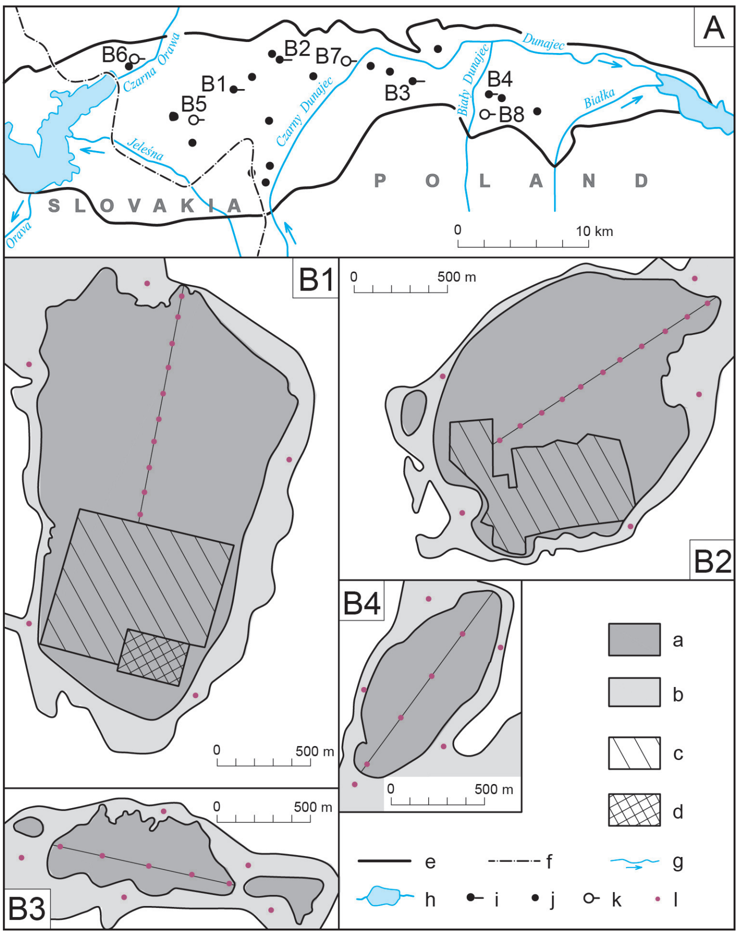

Figure 6. Location of sites with peat sampling in order to determine capillary water capacity of peat by volume (Pwv) in percentages. A – location of sampling in the Orava – Nowy Targ Basin; all the residual raised bog domes with post-peat areas are marked as well as selected fens (B1 – Puścizna Wielka, B2 – Baligówka, B3 – Przymiarki, B4 – Bór na Czerwonem, B5 – Puścizna near Pusta Polana, B6 – near Otrębowskie Brzegi, B7 – near Puścizna Rękowiańska, B8 – near Bór na Czerwonem); B – location of sites with peat sampling on the map of raised bogs (see above). a – residual peat domes, b – young post-peat areas, c – partly excavated peat areas, d – active peat working area, e – basin boundary, f – state boundary, g – main rivers, h – reservoirs, i – residual domes of raised bogs investigated (B1-B4), j – other residual domes, k – fens investigated (B5-B8), l – detailed location of sites with peat sampling within domes and fens

and in fens at 2-3 depths. Peat samples from the greatest depths (from domes and post-peat areas) are composed of fen (*sedge*) peat, whereas samples from smaller depths are composed of raised bog (*Sphagnum*) peat (compare Lipka & Zając 2014). Peat sampling was repeated in 2013 using the same methodology[2].

Water resources in peat bogs, both current and those existing before the beginning of intensive human impact in the Orava – Nowy Targ Basin, were estimated based on the appropriate capacity of peat deposits and values of the volume of capillary water in peat in the volume version (Pwv) in percentages. Based on these values, the maximum amount of water which may be stored in the domes of raised bogs (now in residual domes and post-peat areas) and in fens was estimated.

Based on the data of Polish Hydrological Service from the period 1971-1980, the following characteristic values of discharge in the Piekielnik Orawski catchment (A = 77.1 km^2) were calculated: MLQ – mean low discharge, MQ – mean discharge, MHQ – mean high discharge. This is the only river catchment with a controlled discharge totally located in the boundary of the basin studied (compare Fig. 5). These values were assumed as typical for the area studied. To compare, analogical values were calculated for two neighbouring catchments of similar areas but located at higher altitudes and built of flysch (Lepietnica in the Gorce Mountains and Wielki Rogoźnik in the Gubałówka Foothills, Fig. 2). The aim of this comparison is to confirm the intensive alimentation of rivers in the basin by groundwater in fluvioglacial fans identified in the literature (e.g. Ziemońska 1973; Dobija 1981; Łajczak 2017a). This information is essential as the investigations concern water resources in peat bogs substantially supplied by groundwater outflows.

The calculated value of the index in centimetres of peat bog water retention in the Orava – Nowy Targ Basin was based on the results of the measurement of peat deposit thickness in a relatively dry period at the end of summer and beginning of autumn and on average results of Pwv measurements which were carried out during the whole vegetation season.

[2] Calculations of Pwv values were carried out using the dryer method in the laboratory of the Soil-Science Institute of the Agricultural University in Cracow and Institute of Geography of the Jan Kochanowski University in Kielce.

Results and discussion

Evaluation of the size of the capillary water capacity (Pwv) of peat

The capillary water capacity of peat in the volume version (Pwv) shows little differentiation in the depth profile of the deposit studied. In the case of domes, the deviation of individual values from the mean value does not exceed 5% (compare Łajczak 2013). Even more even values of Pwv were found in the depth profiles in fens. This may be explained by the more intensive water absorption within peat deposits built of sedge peat. The following average Pwv values were obtained, which are the basis for further investigations: peat in domes of raised bogs – 87%, peat in fens – 89%, residual peat deposits in post-peat areas – 82%.

The Pwv value indicates the largest amount of water which may be temporarily stored in a peat deposit. This amount of water is almost always larger than the contemporary water content in the shallowest peat layer and in the acrotelm because during most of the vegetation season part of the water from this layer of the peat bog evaporates, which causes seasonal lowering of the water table in the peat bog resulting in a sinking of the peat bog surface (compare Horawski et al. 1979; Łajczak 2013). This phenomenon is intensified due to peat bog dewatering by drainage ditches. In deeper layers of the catotelm, the water content is stable (Łajczak 2013).

Evaluation of the outer limits of the peat bog in the Orava – Nowy Targ Basin before ca. 1500

The author estimates that until the end of the Middle Ages, i.e. before settlement started around the Orava – Nowy Targ Basin (compare Falniowska-Gradowska 1997), raised bogs and fens together with water-logged areas as places for the potential development of peat bogs might have covered about 1/3 of the basin area which is about 220 km^2 (Fig. 3B). Vast fens surrounded all the peat domes and also covered the valley bottoms. The most intensive fen development occurred in the valley of the meandering Czarna Orawa river which is now transformed into the Orava Reservoir, but until the 19th century this area contained numerous oxbow lakes, peat bogs and swamps (compare *Spezialkarte*... 1894). Raised bogs developed in the basin in a non-synchronous way in the Holocene which resulted in their differing dimensions; the length of most of the peat domes exceeded 0.5 km,

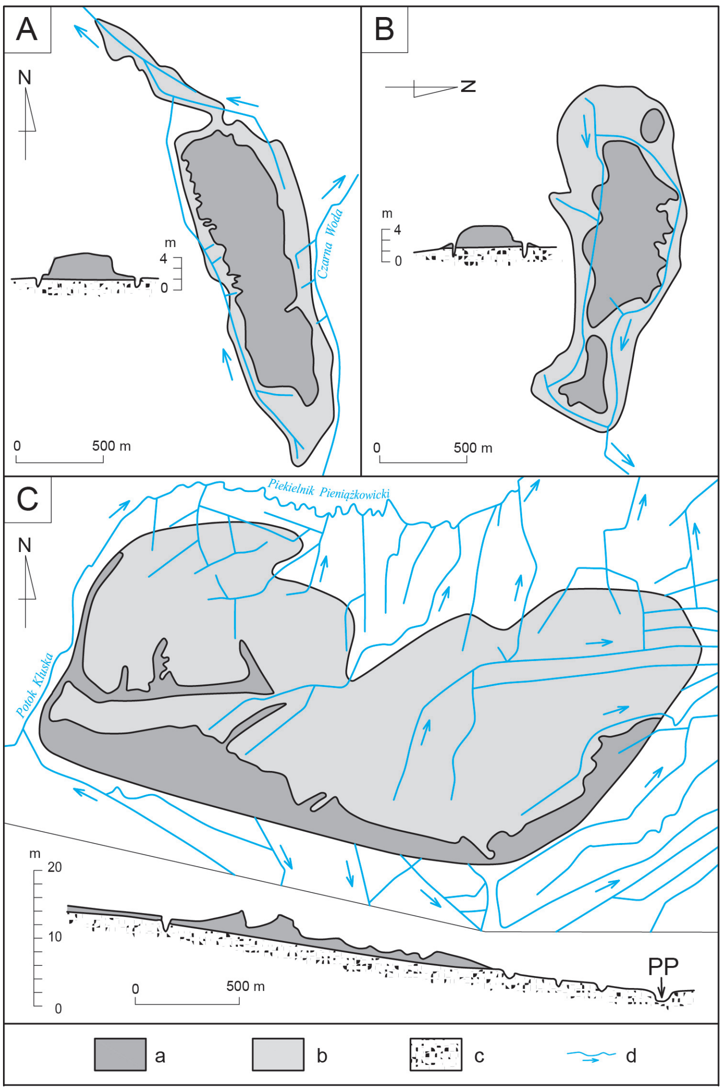

Figure 7. Peat bogs: A – Puścizna Mała, B – Przymiarki, C – Puścizna Rękowiańska as examples of peat bogs substantially drained by drainage ditches in the Orava – Nowy Targ Basin (according to Łajczak 2007). a – residual peat domes, b – young post-peat areas, c – mineral substratum of peat bogs, d – drainage ditches and direction of drainage. Relative height is marked in the peat bog profiles (PP – Piekielnik Pieniążkowicki river)

and the largest one even 6 km. The end of the Middle Ages should be recognised as a period in the Holocene when the area of peat bog in the basin was the largest (Łajczak 2007).

Evaluation of the decrease in area of the peat bog during the last ca. 500 years

Among at least 20 peat domes (whose probable areas in the Orava – Nowy Targ Basin about 500 years ago are shown in Fig. 3B) three features have totally disappeared and the others have become reduced or dismembered. In post-peat areas, the abandoned peat deposit of a thickness usually below 20 cm becomes weathered, which is conditioned by deep drainage ditches reaching the mineral substratum (Fig. 7). The greatest reduction in area occurred in the fens, as they were easily transformed into farmland. The author of the paper estimates that the total area of peat bogs in the study basin decreased threefold during the last 500 years; a similar decrease concerns the area of the peat domes in the raised bogs (compare Fig. 3B, C, Łajczak 2013). At present fens cover an area of 3,450 ha, residual peat domes – 1,312 ha, and post-peat areas with the preserved peat layer – 1,250 ha. The size of the area devoid of peat is 16,000 ha and until the 1990s this area was used for agricultural purposes. Despite such use, habitats of hydrophilous vegetation with a total area of 1,930 ha and with trace amounts of peat are preserved in many places. Such areas are located beyond the limits of contemporary post-peat areas. The cited area of 16,000 ha represents therefore the older post-peat areas, where the peat deposit has been gradually destroyed since the 16th century. This area contains the now destroyed major part of the fens and the only partly affected raised bog domes. Younger post-peat areas (which are simply called post-peat areas in this work) include the rest of the areas degraded by human impact since the 1850s and consist of fragments of peat domes. Peat deposits of extremely reduced thickness have been preserved there. For over 15 years the area called the older post-peat area has been transformed into a wasteland, which favours the development of hydrophilous vegetation and the preservation of detached residual patches of peat. Younger post-peat areas have never been used as a farmland.

Evaluation of water storage in peat bogs until ca. 1500

The volume of water stored in peat deposits before 1500 was estimated by adopting some input data separately for fens and for the domes of raised bogs. Data for the fens include: total area – 18,000 ha, average thickness of peat deposit – 20 cm, total volume of peat deposit – about 36 million m^3, capillary water capacity of peat (as now) – 89%. Data for raised bog domes include: total area – 4,000 ha, average thickness of peat deposit – 400 cm, total volume of peat deposit – about 160 million m^3, capillary water capacity of peat (as now) – 87%. The probable total amount of water which might have been permanently stored in fens in the Orava – Nowy Targ Basin was estimated to be 32 million m^3, and in the raised bog domes – 139 million m^3, which together makes 171 million m^3 of water retained in peat deposits (Fig. 8).

Evaluation of contemporary water storage in peat bogs

The current volume of water stored in the peat cover in the Orava – Nowy Targ Basin was estimated adopting some input data separately for fens, raised-bogs and post-peat areas with the preserved residual peat layer. The data for fens includes: total area – 3,450 ha, average thickness of peat deposit – 50 cm (larger than before, which results from the almost total loss of peat cover with a thickness below 20 cm), total volume of peat deposit – about 17 million m^3, capillary water capacity of peat – 89%. Data for the raised bog domes include: total area – 1,312 ha, average thickness of peat deposit – 4 m, total volume of peat deposit – about 52 million m^3, capillary water capacity of peat – 87%. Data for post-peat areas include: total area – 1,250 ha, average thickness of peat deposit – 20 cm, total volume of peat deposit – about 2.5 million m^3, capillary water capacity of peat – 82%. The total volume of water which is currently stored in the fens in the basin is estimated to be 15.1 million m^3, in raised bog domes – 45.2 million m^3, and in post-peat areas – 2.1 million m^3. The total volume of water currently retained in the peat bogs in the area studied is 62.4 million m^3, which is 2.7 times smaller than 500 years ago (compare Fig. 8).

Index of water storage in peat bogs in the basin – currently and in the past

The estimated index of water storage in peat bogs should be recognised as smaller than the largest water capacity of peat bogs recorded in spring (Łajczak 2013). During this season the surface of peat bogs (especially domes) in the Western Carpathians has a higher elevation than at the turn of summer and autumn (Horawski et al. 1979).

In relation to the whole area of the Orava – Nowy Targ Basin (643 km^2), the index of water storage in peat bogs reaches 10 cm. Before 1500, this index was probably 27 cm. If the area of this coefficient was limited to the part of the basin where all the peat bogs are concentrated (compare Fig. 3B, C), its value should be increased by at least a factor of three.

Evaluation of retention in contemporary lakes

The Orava Reservoir started operation in 1953 and its capacity is 331 million m^3 at the highest water stage. The Czorsztyn Reservoir was commissioned in 1997 and its capacity is 232 million m^3. The total capacity of both reservoirs is 563 million m^3, which is 9 times larger than the contemporary water volume in all peat bogs in the basin, and in relation to the state of peat bogs 500 years ago, it is over 3 times larger.

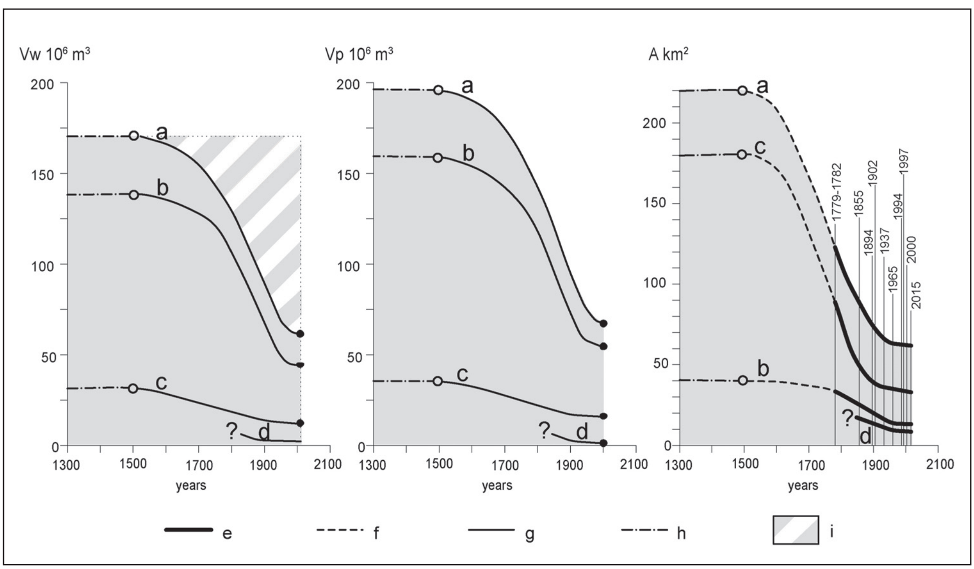

Figure 8. Evaluated decrease of water content in peat deposits (Vw) in the Orava – Nowy Targ Basin since the 16th century compared with the decrease in the total volume of peat (Vp) and total area of peat bogs (A) in this area. Decreasing values of A, Vp and Vw concern: a – total area of peat bogs, b – raised bog domes, c – fens, d – younger post-peat areas; e – course of A values determined on the basis of the analysis of topographic maps, aerial photographs and field studies (years are marked), f – approximate extrapolation into the past (to about 1500) of the A value based on contemporary field observations (explanations in the text), g – course of Vp and Vw values based on data (e) and (f), h – probable course of A, Vp and Vw values before 1500, i – increase in total volume of water lost by peat bogs from 1500 to 2015.

The given value of lake retention is not a permanent value, but it gradually decreases as a result of the progressive silting-up of reservoir basins. The useful lifetime of the Czorsztyn Reservoir was estimated at 710 or 810 years (depending on input data) (Łajczak 1996). In that time, as a result of the filling, the dead and useful capacity, and part flood capacity of the reservoir basin with sediments, its capacity is going to decrease by at least 80%. There are no such data concerning the Orava Reservoir, but taking into account its larger capacity and smaller sediment supply (Banach 1992; Łajczak 2017b), the useful lifetime should be at least twice as long.

Comparison of the index of lake retention and water storage in peat deposits

The index of lake retention in the Orava – Nowy Targ Basin is 88 cm, taking into account the total volume of both reservoirs during the highest water stages, and the basin area of 643 km^2. A summary index of lake retention and water storage in peat bogs is now 98 cm. This value is 90% influenced by storage caused by artificial reservoirs. The volume of water storage indicated in the reservoirs and in the peat deposits should be recognised as very large, which is a distinguishing feature of the Orava – Nowy Targ Basin in the whole Carpathians. In a hypothetical situation, if the water storage in the peat bogs was similar to the state before ca. 500 years ago, the total index of water storage in the reservoirs and in peat bogs would reach 115 cm, with a 23% participation of water in peat.

The large volume of surface water storage in the Orava – Nowy Targ Basin is conditioned by the distinctive hydrogeological situation in this area, and the large capacity of the reservoirs which represent the result of human activity aiming at changing the dynamic discharges of the rivers (rich in water) which drain the area studied (Ziemońska 1973; Dobija 1981; *Hydrogeography*... 1983; Punzet 1991; Dynowska 1995; Łajczak 2007; Chowaniec 2009).

Hypothetical index of water storage in the situation of more intensive dam development in the basin

The index of lake retention in the Orava – Nowy Targ Basin would be even higher if the 1970s and 1980s projects for building new water reservoirs had been completed (compare Fig. 4). The volume of water stored in the basin and its surroundings would amount to over 850 million m^3 (including the two existing reservoirs), with an index of lake retention of 132 cm.

The index of lake retention in the Orava – Nowy Targ Basin would be even larger if the plans for building dams on the Orawa and Dunajec rivers had been completed in their maximum version. In such a situation, the total volume of both existing reservoirs would be 2.5 times larger than it is now (about 1,400 million m^3) with an index of lake retention of 218 cm and, together with the water in peat, 228 cm. These values should be increased by at least 45 cm if the other reservoirs planned in the basin or adjacent areas had been built. In such a situation the basin studied with a lake retention index of 263 cm would represent a large reservoir of artificially stored water incomparable with other similar areas in Poland or the whole Carpathians. Together with the water currently stored in peat deposits, this index would exceed 270 cm.

Changes in water storage in peat bogs in the period 1500-2015

Characteristic changes may be observed in the estimated amount of water stored in the peat bogs studied over the last 500 years which are related to the decrease in the area of peat bog and the decrease of total peat volume which has been documented in the cartographic analyses, field measurements and observations (Fig. 8). The fastest rate of water loss in peats occurred during the period 50-150 years ago. During the last 50 years, due to the decreasing amount of peat exploitation for heating and balneological purposes, the rate of water loss has slowed down and during the last 20 years water loss has almost totally ceased. The course of water loss in the period of 500 years analysed is similar in both fens and the domes of raised bogs and during the last 150 years also in post-peat areas.

Increase of water storage in reservoirs in the second half of the 20th century

In the second half of the 20th century, a new form of water storage commenced in the Orava – Nowy Targ Basin, i.e. retention in reservoirs. In 1997, the total capacity of two water reservoirs reached 563 million m^3, which exceeded by 9 times the amount of water stored in peat. The amount of water in the existing reservoirs would be 22 times larger than the water stored in peats if the capacity of reservoirs reached the originally planned values. If more dams had been built in this area (as was planned), the amount of water in all the reservoirs in 1997 would be 27 times larger than the current water retention in the peat bogs. Attention should be paid to the stepwise increase of total capacity of reservoirs (starting from zero) in the three indicated variants against the background of stable

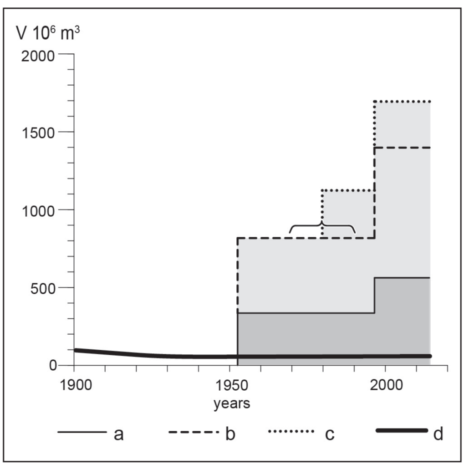

Figure 9. Increase in total capacity of reservoirs (V) in the Orava – Nowy Targ Basin in the second half of the 20th century. a – working reservoirs, b – working reservoirs but with their larger extent as formerly planned (hypothetical version), c – reservoirs formerly planned in this area (hypothetical version including (b)), d – the course of water retention in peat bogs in the basin since 1900

water content in peat deposits since the turn of the 20th century (Fig. 9), which exceeded at that time 60 million m^3 (at the beginning of the 20th century – 100 million m^3).

Water storage in peat bogs versus groundwater outflow from fluvioglacial deposits

The following question may be asked – is there a relationship between a natural form of surface water storage in the Orava – Nowy Targ Basin, i.e. in peat bogs (the development of which is connected with the drainage of deeper water), and the discharge regime in the catchments located exclusively within the boundaries of this basin? These conditions are met in the catchment of the Piekielnik Orawski river (A = 77 km^2) which to a large extent is covered by peat bogs (compare Fig. 2, 3, 5) and is alimented exclusively from fluvioglacial deposits (Łajczak 2007). As compared to the neighbouring, higher located catchments of similar area, i.e. the Lepietnica and the Wielki Rogoźnik, which are built of less retentional flysch sediments, the course of discharge from the Piekielnik Orawski catchment within the range of mean low discharge (MLQ), mean discharge (MQ) and mean high discharge (MHQ) in an annual cycle is the most even (Fig. 10A). This feature of the discharge regime is particularly seen in the minimum value of the quotient of the largest and smallest monthly value in the range MLQ, MQ, MHQ (Fig. 10B). An extremely even discharge course occurs in the annual cycle in the catchment of the Piekielnik Orawski during low discharge values MLQ, when watercourses in the catchment are exclusively supplied by waters flowing out from fluvioglacial deposits. At that time, the quotient of the largest and smallest monthly value of MLQ is only 1.4. Although the range of discharge in the MLQ in the Piekielnik Orawski catchment is smaller than in the catchments compared over a year (compare Fig. 10A), the smallest values of discharge recorded in different seasons (especially in winter) amount to about 2.5 $dm^3 \cdot s^{-1} \cdot km^{-2}$ and they are larger

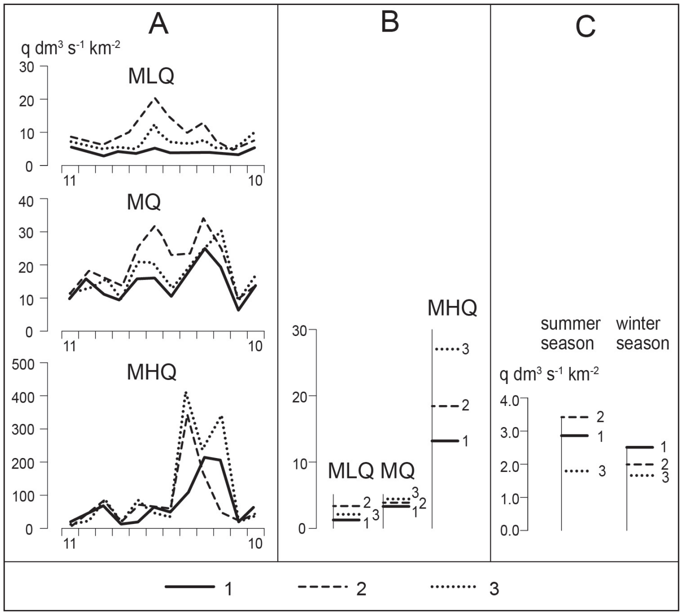

Figure 10. Characteristic discharge values (q) in the range of MLQ, MQ, MHQ of the Piekielnik Orawski river (1) which represents the Orava – Nowy Targ Basin, with the discharges of the Lepietnica river (2) and the Wielki Rogoźnik river (3) which represent the Beskidy Mountains and Gubałówka Foothills respectively, shown in the background. A – seasonal course of MLQ, MQ, MHQ values (successive months of the hydrological year are marked on the horizontal axis: 11 – November, ..., 10 – October), B – quotient of the largest and smallest monthly values in the range MLQ, MQ, MHQ of the above-mentioned rivers, C – the smallest absolute recorded discharge in these rivers in the summer season and in the winter season. MLQ – mean low discharge, MQ – mean discharge, MHQ – mean high discharge

than in the neighbouring, higher located areas (Fig. 10C).

The great abundance of groundwater in the Orava – Nowy Targ Basin results in a high percentage of underground supply in rivers (40-50%), which is slightly less than in the Tatras (> 50%) but more than in the Beskidy Mountains (< 30%) (Dobija 1981). The minimum discharge values of 50% probability cited in the literature reach 4 $dm^3 \cdot s^{-1} \cdot km^{-2}$ in the basin (Punzet 1991; Dynowska 1995) and they are larger by only 1/3 than the absolute minimum discharge values given above relating to the Piekielnik Orawski catchment located in this basin. Minimum discharge in the Orava – Nowy Targ Basin reaches one of the highest values in the Polish Carpathians and only the Tatras and large landslide areas show greater values (Dobija 1981; Dynowska 1995; Chowaniec 2009).

Conclusions

The features of groundwater discharge in the Piekielnik Orawski catchment presented as a representative catchment in the Orava – Nowy Targ Basin, provide a high level and stable moistening of the surface of fluvioglacial fans, which results in peat bog development on a large scale. The large resources of groundwater in the fluvioglacial deposits in the Orava – Nowy Targ Basin provide a large volume of water storage in the vast peat bog in this area.

Human activity in the Orava – Nowy Targ Basin resulted in bidirectional changes in water storage. During the last ca. 500 years, the volume of water stored in the peat has decreased threefold as a result of anthropogenic exploitation of peat bogs or the destruction of parts of or even whole features, from 171 million m^3

to 62.4 million m^3. Despite this fact, the basin known as the Orava-Podhale Peatland is still of note in terms of the amounts of water stored in vast peat bogs in the context of the whole of the Carpathians.

In the second half of the 20th century, a new form of water storage appeared in the basin. Two dams were built retaining reservoirs with a total capacity of 563 million m^3, which exceeds by 5 times the amount of water retained in peat. If the more ambitious project of dam construction formerly planned in the basin had been completed, the total capacity of the reservoirs would have exceeded 27 times the present retention of water in the peat.

The perception of the drastic shrinkage of the area of peat bog in the Orava – Nowy Targ Basin and the reduction of water resources stored in the peat deposits as an ecological disaster does not only have an ethical dimension but also refers to disturbances in the functioning of abiotic and biotic elements of nature (compare Charman 2002). Compensation of the water resources lost in peat in this basin in form of considerably larger artificial lake retention has, however, only got an economic dimension.

The perspective of long lasting water storage in reservoirs in the Orava – Nowy Targ Basin, i.e. longer than 700 years (provided that the dams remain sound?), is optimistic.

Side by side with the decreasing water storage in the reservoirs in the Orava – Nowy Targ Basin, an increase of water volume in peat may take place, providing there is a total discontinuation of peat exploitation and drying out of peat. The changes in peat bogs currently observed indicate increasing water resources in post-peat areas (compare Łajczak 2007, 2013). Taking into account an optimistic scenario of the future state of peat bogs in this basin, and including a mean rate of increase of peat thickness in the Polish Carpathians of about 0.5 $mm \cdot a^{-1}$ (Żurek 1987), an increase of 50 cm in the peat layer (which makes about a 43 cm water layer in the deposit) may take 1,000 years. This theoretical increase of the amount of water in the peat layer does not compensate, however, for the amount of water lost due to the silting of the reservoir basins.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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