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Role of land relief and structure in the formation of peat bogs in mountain areas, as exemplified by the Polish Carpathians

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Abstract: It has been often argued that the formation of peat bogs in the mountains is predominantly influenced by a humid climate. Although in many mountains precipitation during the vegetation growth season is greater than evaporation, bogs, especially of the raised type, do not cover all gently sloping areas and often develop only within certain landforms. Local hydrological conditions determined by land relief and structure are the most crucial factor in the development of bogs in such areas. Peat bogs of the Polish Carpathian Mountains demonstrate that bogs, irrespective of altitude, develop mainly in concave landforms or below convex morphological recesses, where outcrops of poorly permeable rocks offer numerous low-capacity but stable outflows of groundwater that continuously humidifies the slopes lying below thus supporting the formation of habitats for hydrophilic plants. This research project covered the parts of the Polish Carpathians having the largest number of bogs, thus allowing local-scale analysis of their location in relation to the lithological, geomorphological and hydrogeological properties of the substratum. It is assumed that an assessment of the influence of substratum on the location and formation of peat bogs is only correct when the coverage of the individual mires in the period preceding their anthropogenic degradation is known. Only then is it possible to establish what types of bedrock and which landforms are most favourable for bog formation.

Key words: raised bog, Carpathian Mountains, Beskidy Mountains, Tatra Mountains, Orawsko-Nowotarska Basin

Introduction

For a bog to develop, specific climatic, geological, geomorphological, hydrographical and hydrogeological conditions must be met (Tołpa 1949, Maksimov 1965, Grosse-Brauckmann 1974, Lowe, Walker 1997, Tobolski 2000, Chairman 2002, Ilnicki 2002, Łajczak 2013). The problem was first analysed by Senft (1862), who divided bogs in terms of water supply into low bogs and raised bogs. As a result of further studies, more types of peat bog were distinguished: limnogenous, fluviogenous, topogenous, soligenous and ombrogenous (Żurek, Tomaszewicz 1996, Tobolski 2000, Ilnicki 2002). In mountain areas where precipitation greatly exceeds evaporation, vast blanket bogs develop, covering ridges, slopes and the feet of the slopes (Bower 1961, Rawes 1983, Mallik *et al.* 1984, Carling 1986, Evans 1989, Cooper, McCaan 1995, Shaw *et al.* 1997, Bragg, Tallis 2001). On the other hand, in those mountains where precipitation slightly exceeds the amount of evaporation in the vegetation growth period, bog formation depends on stable yet low-volume outflows of groundwater, permanently humidifying the slopes located below, which then form a habitat for hydrophilic vegetation (Łajczak 2009, 2011a, b, 2013). In the area surrounding such outflows, with a seepage-type water circulation, shallow bogs are the first to develop (Gore 1983). As the shallow peat deposit grows thicker and consequently the contact of the bog surface with minerotrophic waters is reduced, oligotrophication and acidification of the habitat occur, which results in the transformation of the bog into a raised bog (Gore 1983, Tobolski 2000, Ilnicki 2002).

Of all raised bogs, mountain bogs are characterised by the most complex conditions for their development. Mountain raised bogs occur on ridges, slopes and valley floors (Kaule, Göttlich 1976, Obidowicz 1985, Łajczak 2007, 2011a, b, 2013, Obidowicz, Margielewski 2008). The classification of mountain bogs and conditions for their development are discussed by Früh, Schröter (1904), Sjörs (1948), Gams (1958), Barsiegan (1974), Kaule (1974), Kaule, Göttlich (1976), Ringler (1981), Obidowicz (1990), Łajczak (2007, 2011a, 2013). Different aspects of their geomorphological development are discussed in works by the following authors: Bower (1961), Rawes (1983), Mallik *et al.* (1984), Evans (1989), Cooper, McCaan (1995), Rhodes, Stevenson (1997), Shaw *et al.* (1997), Bragg, Tallis (2001), Dykes, Warburton (2007), Łajczak (2007, 2011a, 2013). The least investigated issues relating to the development of raised bogs include the relation between their location and local landform features and water phenomena.

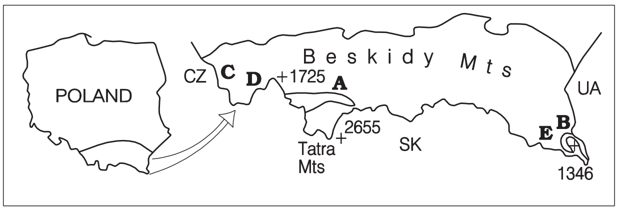


Fig. 1. Areas in the Polish Carpathians investigated
A – Orawsko-Nowotarska Basin, B – bottoms of the San and Wołosaty valleys in the Bieszczady Mountains, mountain ridges in: C – Beskid Śląski, D – Beskid Żywiecki, E – Bieszczady

The problems outlined in this study are discussed on the basis of the example of raised bogs in the Polish part of the Carpathian Mountains. The number of raised bogs in these mountains is low compared to the northern, lowland part of Poland which has a young-glacial land relief (Żurek 1983, 1987, Dembek *et al.* 2000, Dembek, Piórkowski 2007). Locally, the number of bogs is large enough for their location to be analysed on the basis of the lithological, geomorphologic and hydrogeological properties of the substratum. Most bogs in these areas of the Polish Carpathians have an area of less than 1 ha, with only a few being larger than 100 ha (Łajczak 2007, 2009, 2011a, 2013). They occur on hilltops, slopes and in some mountain valleys and basins. Bogs located on ridges are for the most part ombrogenous in nature, while the more numerous slope bogs are soligenous. The lowest located bogs are fluviogenous and topogenous, and locally there are also ombrogenous ones (Kukulak 1998, Haczewski *et al.* 1998, 2007, Margielewski 2006, Dembek, Piórkowski 2007, Obidowicz, Margielewski 2008, Łajczak 2009, 2011a, 2013). This study covers bogs in the Orawsko-Nowotarska Basin, on the floors of the upper San River and the Wołosaty River valleys, on the mountain ridges of the Beskid Śląski, the Beskid Żywiecki and the Bieszczady Mountains (Fig. 1).

Study area

The largest bog areas in the Polish Carpathian Mountains are those in the Orawsko-Nowotarska Basin. The Basin, which has an area of 600 km^2, is the only intramontane basin in the Carpathian Mountains with an extensive development of raised bogs (Łajczak 2007) (Fig. 2A). The Basin lies between the high-mountain massif of the Tatra Mountains and the Beskidy Mountains and is inclined northwards. The bogs in the Basin developed on glaciofluvial fans and on river terraces at altitudes of 590–770 m above sea level, lying from 5 to 40 m above river channels. They cover a poorly permeable 2-metre thick layer of clay, sitting on strongly hydrated gravels. The formation of bogs in the Basin is enhanced by its cool and humid climate (precipitation of approx. 1,000 mm). The average thickness of peat in domes exceeds 3 m, occasionally reaching as much as 11 m. The 100 km^2 area of the Orawsko-Nowotarska Basin has 5 fragments of raised bog preserved. This is several times more than the average figure for the entire area of the Polish Carpathians (Żurek 1987). Raised bogs cover 5% of the Basin area, and together with the low bogs – 12%. According to Żurek (1983), the latter figure exceeds the average Polish bogland coverage ratio by a factor of 3. Prior to settlement activity in the late Middle Ages, bogland might have occupied over 40% of the area (Łajczak 2007, 2013). As a result of bogland shrinkage, mainly due to peat extraction and efforts at drainage, fragmentary peat domes, post-peat

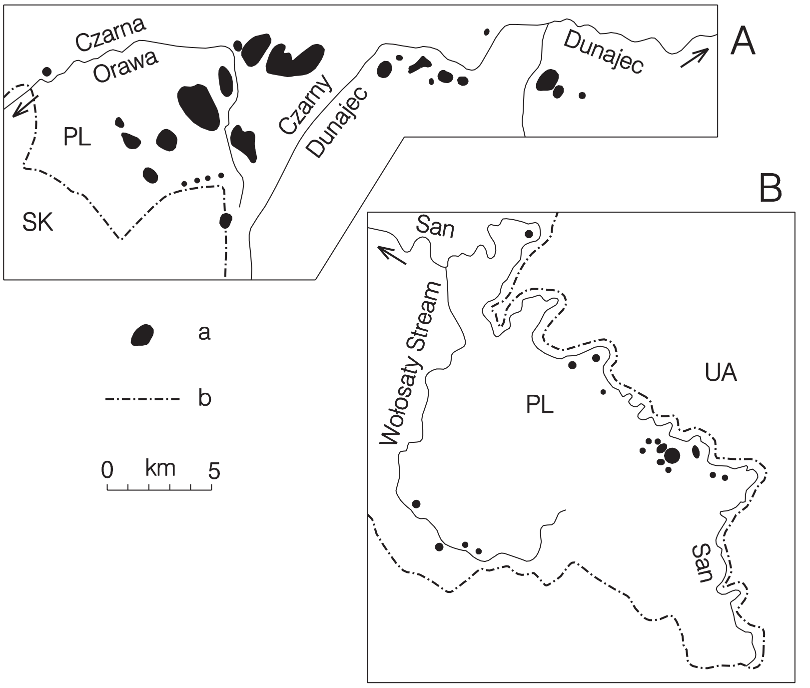


Fig. 2. Peat bogs in the Orawsko-Nowotarska Basin (A) and in valleys of the upper San and Wołosaty rivers in the Bieszczady Mountains (B)
a – current coverage of bogs, b – state border

areas with trace peat deposits and low bogs currently cover 70 km^2 (Łajczak 2006, 2007). Hydrogenic habitats with no peat-forming process cover approx. 25% of the Basin area (Dembek *et al.* 2000). Despite the substantial shrinkage of its bogland in the last 500 years, the peat-covered area in the Orawsko-Nowotarska Basin, referred to as the Orawsko-Podhalańskie Peatlands, can nevertheless be compared with some of the largest peat-covered areas in other massifs in Europe (Żurek 1983, 1987, Dembek *et al.* 2000, Ilnicki 2002, Łajczak 2006, 2007, 2011a, 2013).

The bottoms of the upper San and Wołosaty valleys in the Bieszczady Mountains, which have a cumulative area of 13 km^2, feature remnants of 17 raised bogs, which translates into as many as 138 bogs when recalculated for a comparable area of 100 km^2 (Fig. 2B). In terms of the concentration of raised bogs, the bottoms of the Bieszczady valley are far ahead of the Orawsko-Nowotarska Basin. However, the bogs in the Bieszczady are much smaller and surrounded by narrower post-peat areas. Fragments of peat domes and post-peat areas cover 4% of the valley floors. Bogs are present at an altitude of 550–700 m above sea level and extend over post-glacial terraces and alluvial fans, lying from 5 to 8 m above river channels. The average thickness of peat does not exceed 3 m, with the bog substratum formed by a layer of silt atop gravel. The precipitation in the area is 1000–1200 mm. Most bogs located at the feet of slopes are recharged by groundwater seepage (Łajczak 2011a, 2013). Currently, the cumulative area of peat domes, post-peat areas and the adjacent low bogs does not exceed 1 km^2 (Łajczak 2011a). Hydrogenic habitats not undergoing the peat-forming process and located in their vicinity cover 5% of the valley bottoms (Dembek *et al.* 2000).

In the Polish Carpathian Mountains, valley bogs on substratum overlain by moraines can be found exclusively in the Tatras. Most frequently, they are present between the ridges of lateral moraines and the valley slopes (e.g. in the Pańszczyca Valley) and between the ridges of recessional moraines (the largest such area is that of the lower part of the Sucha Woda Valley) (Baumgart-Kotarba, Kotarba 2001). The parent material of these bogs is formed by poorly permeable material deposited on moraine debris.

Peat bogs on slopes occur above moraine ridges (the Tatra Mountains) and in depressions formed by the melting of dead ice (numerous sites in the Tatras and on the northern slope of Mount Pilsko in the Beskid Żywiecki). In the Beskidy Mountains, peat bogs are found on slopes in the following situations: on flat areas and in landslide niches, in depressions surrounding springs, at mountain ridge passes and on cryoplanation terraces – mostly at the base of steep slopes. The substratum of bogs on slopes is formed by locally deposited fine-grain eluvium, which, in the Flysch Carpathians, is located on shale rock outcrops. The above morphological situations always involve outflows of groundwater, even minute ones, which hydrate the area surrounding the peat bogs and the nearby hydrophilic vegetation habitats not yet undergoing the peat-bog forming process.

Outline of previous research on conditions for peat bog formation in the Carpathian Mountains

Information on the conditions of bog formation in the Polish Carpathian Mountains mainly cover the Orawsko-Nowotarska Basin, and to a lesser extent, valleys in the Bieszczady Mountains. As regards the other areas under study, information is only available for selected peat bogs within landslides. Even as late as the turn of the 21st century, the issue was not addressed by mainstream studies and its importance was marginalised, as the researchers' main focus was on the palaeography of peat bogs, their structure, vegetation, economic use or human-induced changes (Staszic 1815, Zejszner 1848, Hołowkiewicz 1881, Gustawicz 1883, Rehman 1895, 1912, Niezabitowski-Lubicz 1922, Szafer 1928, Korczyńska 1952, Mirska 1956, Obidowicz 1988, 1989, Koczur 1996, Lipka 1999, Łajczak 2001, 2002). It has been only in the last two decades that growing attention has been paid to the conditions of peat bog formation in the Polish Carpathians, initially in the Bieszczady Mountains (Haczewski *et al.* 1998, 2007, Kukulak 1998), and later in the Orawsko-Nowotarska Basin (Łajczak 2006, 2007, 2009, 2011a, 2013), as well as in selected peat bogs in the Beskidy Mountains (Margielewski 2006). While the level of understanding of the conditions of peat bog development in the Orawsko-Nowotarska Basin and in the Bieszczady valleys, with special focus on the role of the relief and structure of the parent material, may be considered satisfactory, it is of note that there is hardly any specific information on the development of peat bogs located on slopes and ridges in the Carpathians.

The impact of the parent material on the development of peat bogs in the Orawsko-Nowotarska Basin and in the Bieszczady Mountains is being increasingly investigated thanks to knowledge about land relief in bog areas. The gradual uncovering of the mineral substratum of peat bogs as a result of mining, and the growing number of drillings made in peat deposits allow the locations where peat bog formation has begun to be identified (Baumgart-Kotarba 1991–92, Kukulak 1998, Haczewski *et al.* 1998, 2007, Baumgart-Kotarba, Kotarba 2001, Łajczak 2007, 2009, 2011a, 2013). Such locations benefit from groundwater outflows, which remain active once the overlaying peat is removed. Geomorphological and hydrographical mapping of peat domes, post peat areas and their surroundings play a crucial role in this respect (Łajczak 2007, 2009, 2011a). Of all the natural factors relevant to bog development within the areas under study, poor permeability of the underlying layer of clay has often been stressed, while the role of climate overestimated (Staszic 1815, Zejszner 1848, Hołowkiewicz 1881, Niezabitowski-Lubicz 1922, Halicki 1930, Korczyńska 1952, Baumgart-Kotarba 1991–92, Kukulak 1998, Haczewski *et al.* 1998, 2007). Little attention has been paid to local geomorphological and hydrogeological factors affecting bog formation. The role of neotectonics and the distribution of watercourses in the process of peat dome expansion has been disregarded. The author's research indicates that bogs started to develop in locations favoured in geomorphological and hydrogeological terms, where peat domes started to grow after the formation of low peat bogs.

Aim of studies

The aim of this study is to explain the role of land relief and structure, as well as the hydrogeological conditions of the development and location of peat bogs, especially raised bogs, located on ridge tops, slopes, the floors of mountain valleys and basins in the Polish Carpathians, i.e. places with a variable excess of precipitation over evaporation in the vegetation growth season across the elevation profile. Thus, this study addresses the role of land hydration in peat bog expansion and explains how expanding raised bogs have changed the land relief and location of watercourses on a local scale.

Data used and methods

This study is based on the results of the author's own geomorphological and hydrographical mapping of peat domes, post-peat areas, low bogs and their surroundings, along with the areas adjacent to the neighbouring watercourses in the Carpathian areas under study. Use was also made of studies on the location of peat bogs in the Tatra Mountains and within selected landslides in the Beskidy Mountains by other authors. Changes in the coverage of peat bogs in the last 230 years were assessed based on maps from 1779–82, 1855, 1894, 1937, 1965 and 1997, and for the last 50 years, also on the basis of aerial photographs. The use of GPS technologies allowed the current extent of individual peat bogs and their location relative to landforms and groundwater outflows and watercourses to be established. The permeability of the mineral substratum of peat bogs was established by means of the Burger cylinder method. Peat thickness was investigated by drilling, while information on the greatest thickness was taken from literature (Baumgart-Kotarba 1991–92, Lipka 1999). During field studies attention was paid to the location of remnant peat deposits outside the locations where peat is present in a compact form, especially in areas where peat mining was discontinued before ca. 1850. The information allowed the previous coverage of peat domes to be established, which was often greater than that shown by the earliest maps.

The relief of the surface underneath the layer of peat was analysed on the basis of the author's own drillings in the bogs under investigation, based on literature (Horawski *et al.* 1979, Wójcikiewicz 1979, Baumgart-Kotarba 1991–92, Kukulak 1998, Haczewski *et al.* 1998, 2007, Lipka 1999), and data from the Peat Company in Czarny Dunajec. This provided information on the geomorphological factors affecting bog development, beginning with the locations where the process was initiated. Observation of exhumed landforms within post-peat areas reveals the spots where the mineral substratum was covered by the thickest layer of peat, i.e. where the peat formation processes started (Łajczak 2006, 2007, 2009).

Based on the above research, the author determined the interdependence between the structure of the shallow substratum of bogs, the hydrogeological characteristics of the parent material, local land relief, and the location of surface water phenomena in the vicinity of the bogs under study. On that basis, the locations where peat bogs are likely to originate were indicated. The likely spread of peat domes prior to their anthropogenic degradation was established. The analysis involved observation of local land relief and the distribution of groundwater outflows and watercourses. The location of hydrogenic habitats not undergoing the peat-forming process shows where peat bogs are likely to form.

Results

The assessment of the impact of the abiotic environment on the development of raised bogs and their distribution within the areas of the Polish Carpathians under study began with the establishment of the size and location of the peat bogs preserved in their natural form. For anthropologically degraded bogs, the perimeters of the remaining peat dome and of the post-peat areas were determined. The next stage was to map the likely coverage of individual anthropogenically degraded raised bogs at the time when they had not yet started shrinking. It was assumed that peat bogs located on the hilltops and slopes of the Beskidy Mountains, as well as all peat bogs in the Tatra Mountains have not been economically exploited to date as they are not easily accessible, and that their coverage has not changed. The area of the valley bogs in the Beskidy Mountains, and even more so, in intramontane basins, has shrunk. By analysing the geomorphological and hydrographical situation within the original bog area and in its surroundings, one can indicate the likely spots where the peat bog formation process began and explain how the build-up of peat domes changed the local land relief and watercourses.

Geomorphological location of peat bogs and their current extent

Peat bogs on the ridges and slopes of the flysch Carpathians

In the flysch Carpathians the highest located peat bogs are found at ridge tops and slopes, and are present on the following landforms (Fig. 3): cryoplanation terraces, mountain passes, structural flats on slopes, depressions surrounding springs, flat areas and depressions created by landslides, and hollows arising from the melting of relic-ice. Peat bog locations in the Carpathians are present at altitudes where precipitation in the vegetation growth season is over twice and locally even four times higher than evaporation (Kowanetz 1998). Despite the very humid climate, bogs occur in specific geomorphological conditions which points to the crucial role of local land relief and stable groundwater outflows in the vicinity of poorly permeable rock outcrops in the peat-formation process. The groundwater outflows permanently humidify the slopes located below them, thus forming a habitat for hydrophilic vegetation.

On the highest elevation ridges of the flysch Carpathians, small bogs develop on cryoplanation terraces. They are mostly present in the Beskid Żywiecki (Mts. Babia Góra, Pilsko, Lipowska), in the Beskid Śląski (Skrzyczne, Barania Góra) and in the Bieszczady Mountains (Tarnica). These mini bogs, usually having an area of several ares and thickness of 30 cm, are found on the outcrops of shale rock inserts in sandstone where permanent groundwater seepage occurs. Some bogs covering sandstone eluvium lying on a shale rock substratum are supplied exclusively by rainwater. They create a masking coat over rock debris located underneath. Peat bogs located on slopes within cryoplanation terraces are hanging bogs. Other locations where smaller bogs are usually present on ridges are passes where stable groundwater seepage occurs. Some of these bogs are accompanied by miniature lakes. Only a very few bogs located on passes reach an area of several hectares and a thickness of 3 m. Bogs on structural flats of slopes develop on shale rock substrata and are fed by numerous groundwater outflows. The largest such bogs are scattered on the slopes of Mts. Babia Góra and Pilsko in the Beskid Żywiecki Mountains. They are shallow (up to 1 m) but have an area of several to more than ten hectares (Fig. 4). Bogs developed on the sides of depressions surrounding springs are known in Poland as hanging peat bogs. As with the previous group of bogs, they have a very variable surface, a thin layer of peat and are present across a wide range of elevations up to 1,200 m above sea level. They are fed by an exceptionally large number of groundwater outflows. The largest such bogs occur near the sources of the Biała and Czarna Wisełka rivers, as well as at the foot of Mt. Barania Góra in the Beskid Śląski Mountains. Bogs developed within the numerous landslides in the flysch Carpathians represent the most numerous group, have a thickness of up to several metres, but, as a rule, their individual surface area does not exceed one hectare (Łajczak 2004, 2011a, b, Margielewski 2006). They are present across a range of altitudes, usually in the bottoms of landslide niches and in depressions within landslide tongues. These bogs are also fed by groundwater seepage, with the substrata formed by fine-grain and impermeable lake deposits. Some of these bogs show the characteristics of hanging peat bogs. Bogs

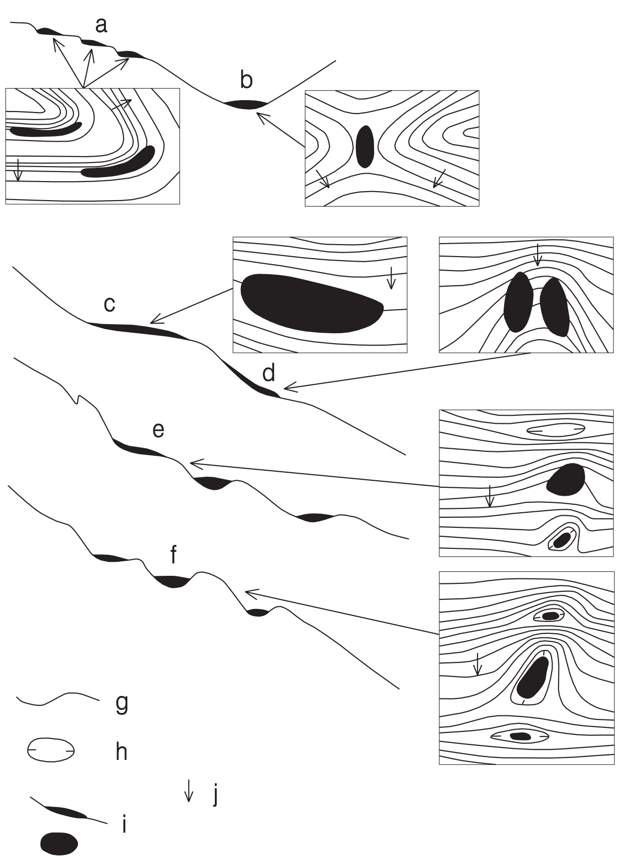


Fig. 3. Typical locations of peat bogs on ridges and slopes in the Beskidy Mountains

a – on cryoplanation terraces, b – within passes, c – on structural flats of slopes, d – in spring niches, e – on landslide flats and depressions, f – in hollows from melting of dead ice g – contour lines, h – land depressions, i – peat bogs (slope profile and plan), j – slope inclination

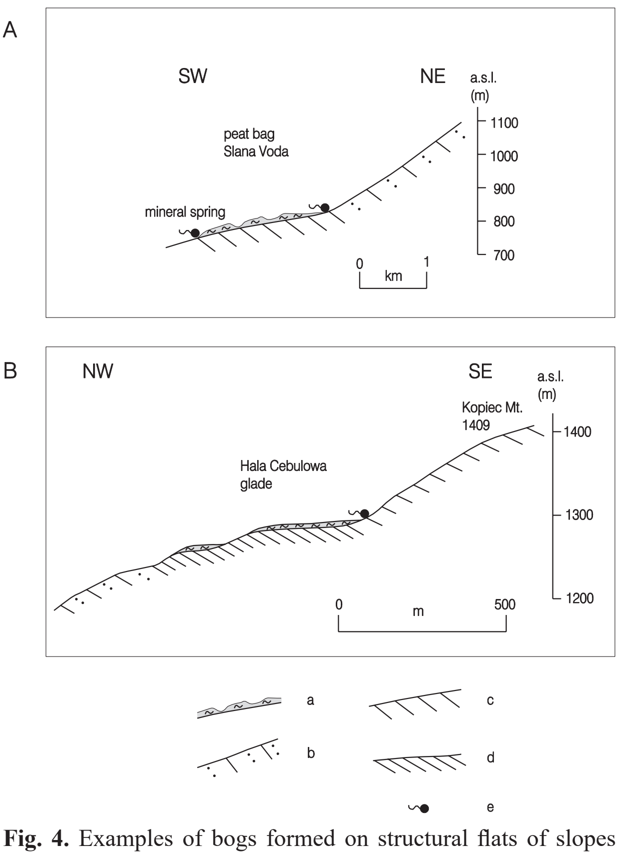


Fig. 4. Examples of bogs formed on structural flats of slopes in the Beskidy Mountains: A - bog on the slope of the Babia Góra massif, B – bog on the slope of the Pilsko massif (both located in the Beskid Żywiecki)

a – bog, b – magura sandstones, c – hieroglyphic beds, d – slate, e – groundwater springs and seepage developed in depressions formed by the melting of dead ice on the northern slope of Mt. Pilsko in the Beskid Żywiecki Mountains, which occur at an altitude of approx. 1300 m above sea level, should be considered unique to the Beskidy Zachodnie (Fig. 5). The feeding of this group of bogs and the nature of their substratum is similar to bogs in landslide depressions (Łajczak 2011b).

Peat bogs in the high-mountain massif of the Tatra Mountains

In the high-mountain massif of the Tatra Mountains, the surplus of precipitation over evaporation is even greater than on the highest mountain slopes in the Beskidy Mountains (Kowanetz 1998). Despite this, in this area bogs are present in depressions overlain with impermeable fine-grain material and are fed by stable groundwater outflows. The first numerous group of bogs in the Tatra Mountains are those located between the ridges of lateral moraines and valley slopes. The largest number of such bogs are present in the Pańczyca River Valley. Another group comprises bogs developed between the ridges of recessional moraines in the lower stretches of the main valleys. Many such bogs occur in the Rybi Potok Valley. However, the most distinguished feature is the moraine amphitheatre in the lower section of the Sucha Woda Valley, with over 20 bogs in hollows, the origins of which are usually attributed to the melting of dead ice (Baumgart-Kotarba, Kotarba 2001) (Fig. 6). Because of the occurrence of carbonate rock underneath the glacial sediments in this part of the Tatra Mountains, the creation of the depressions occupied by the bogs is likely to have been influenced by karst processes. Some of these depressions may be considered to be reproduced by karst sinkholes.

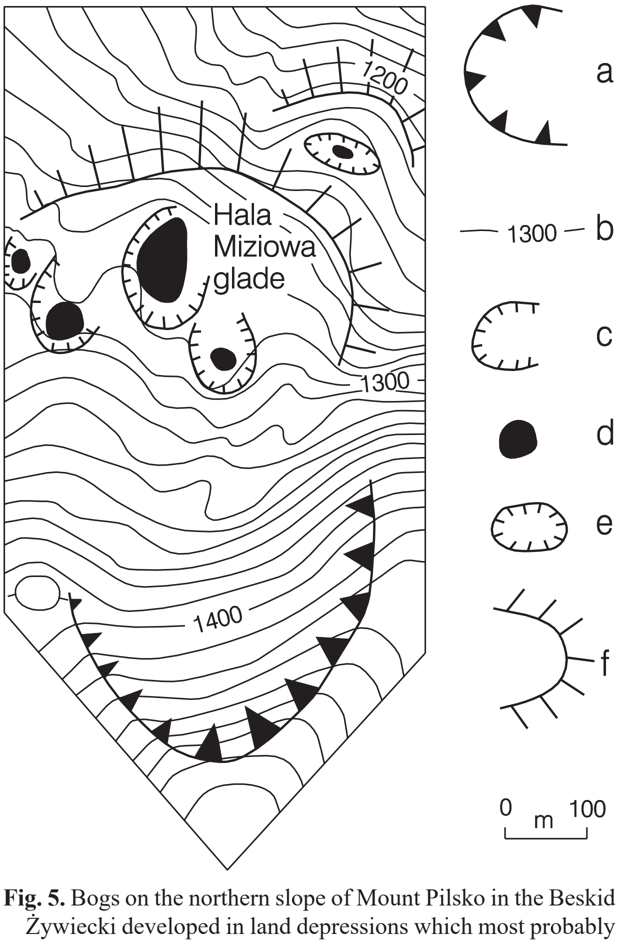


Fig. 5. Bogs on the northern slope of Mount Pilsko in the Beskid Żywiecki developed in land depressions which most probably originated from melting of dead ice

a – niche borders (former glacial undercut), b – contour lines, c – depressions from melting of dead ice, d – bogs, e – depressions with no outflows, f – moraine front

Valley peat bogs in the Bieszczady Mountains

Valley peat bogs in the Polish part of the flysch Carpathians are scattered predominantly on high terraces at the base of slopes. Usually, they have an area of less than 1 hectare and only some may be classified as raised bogs. In two valleys of the Polish flysch Carpathians alone – in the upper San River valley and in the Wołosaty River valley in the Bieszczady Mountains – there are 17 raised bogs on which a dome has formed. They are located at an altitude of 550–700 m above sea level, where precipitation in the vegetation growth season exceeds evaporation by not more than 50%. Each of the bogs in these valleys has been slightly reduced by human activity, therefore the minimally decreased peat domes with the post-peat areas mark the borders of the individual bogs from before their economic exploitation (Łajczak 2011a). The current area of individual peat dome fragments in the Bieszczady valleys under inves-

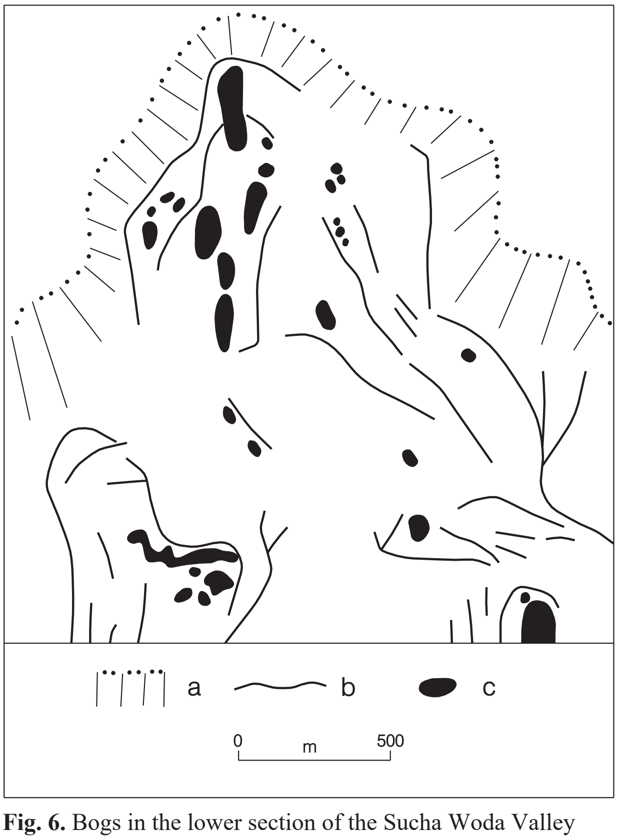


Fig. 6. Bogs in the lower section of the Sucha Woda Valley

a – extent of terminal moraine, b – recessional moraines from the last glaciation, c – bogs and lakes in different stages of bog formation (after Baumgart-Kotarba, Kotarba 2001) tigation ranges between 0.6 and 9.0 ha. All raised bogs in the area occur within landforms where groundwater seeps out above poorly permeable forms, thus providing permanent humidity for hydrogenic habitats. These bogs (reduced peat domes + post-peat areas) occur on the Vistulian terrace at the base of slopes at an elevation of 5–8 meters above river channels, on Holocene alluvial fans overlying the terrace, and in paleochannels. The preserved fragments of peat domes and post-peat areas cover only 4% of the valley bottoms of the two rivers in the Bieszczady Mountains. The average thickness of peat in domes does not exceed 3 m (Łajczak 2011a, 2013).

Peat bogs in the Orawsko-Nowotarska Basin

The Orawsko-Nowotarska Basin is distinguished by a large number and square area of raised and low type bogs. Currently, there are 22 remnants of peat domes with an area ranging between 1 and 356 ha each. These domes are remnants of much large ones, after having been reduced, to different extents, in the process of peat mining, including their fragmentation and drainage with a dense system of drainage ditches (Łajczak 2011a). At least three raised bogs had been completely exploited by the end of the 19th century. The area also has 5 naturally preserved bogs, which are in the initial phase of raised bog formation. The vast bogland area in the Czarna Orawa River valley in the western part of the Basin, shown on the “Die Spezialkarte ….” map (1894), lies on the bottom of the Orawa Reservoir constructed in 1954.

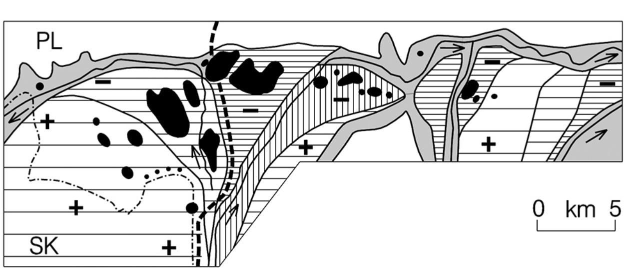
Remnants of peat domes with post-peat areas in the Orawsko-Nowotarska Basin are present on fragments of various-age Quaternary glaciofluvial fans, with the highest number in the Czarny Dunajec River fan, which occupies 2/3 of the Basin area. The remaining fragments of peat domes occur on post-glacial terraces of the Czarna Orawa and Czarny Dunajec valleys (Łajczak 2007, 2011a) (Fig. 7). Degraded bogs concentrate in the younger, i.e. central, northern and eastern part of the Czarny Dunajec River fan, which may be explained by the neotectonics and land relief (Vanko 1988, Zuchiewicz 2010). The deeper drainage of groundwater in the western part of the glaciofluvial fan of the Czarny Dunajec River, which is being uplifted and incised by erosion, is not favourable for bog formation. On the remaining downthrusted area of the fan, groundwaters are shallow and their outflows feed extensive bogs.

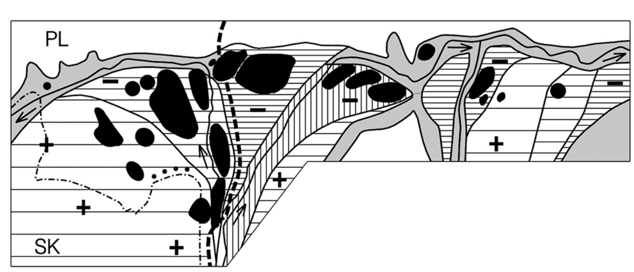
In the Orawsko-Nowotarska Basin, precipitation in the vegetation growth season only slightly exceeds evaporation (Kowanetz 1998). The fact that most of the bogs are located in concave landforms proves that geological-geomorphological-hydrological conditions are crucial for the functioning of hydrogenic habitats within the area. Six geomorphological situations were distinguished in the Basin, where bogs are anthropogenically degraded to different extents. Except for the first situation, bogs are fed by groundwater seepage throughout their development. Ranging from the highest to the lowest areas in the Basin, bogs are present on or in the following landforms:

1. watershed zones at an elevation of 5–40 m above watercourse channels,
2. spring niches, bottoms and slopes of shallow erosion-induced incisions,
3. paleochannels of the Czarny Dunajec River,
4. Quaternary terraces, and particularly their fragments at the base of the edge of the higher terrace,
5. the Vistulian terrace in areas with multiple shallow groundwater outflows,
6. post-glacial terraces of the Czarna Orawa and Czarny Dunajec rivers.

Reconstruction of the extent of raised bogs prior to anthropogenic degradation

The likely extent of individual bogs prior to anthropogenic degradation was mapped exclusively for the Orawsko-Nowotarska Basin and for the two valleys in the Bieszczady Mountains mentioned above (Łajczak 2011a). Figure 8 presents the original extent of bogs in the first of these areas. Compared to the present-day situation, it can be observed that the size of bogs has shrunk to various degrees, three bogs have completely disappeared and peat domes have been fragmented into smaller features.





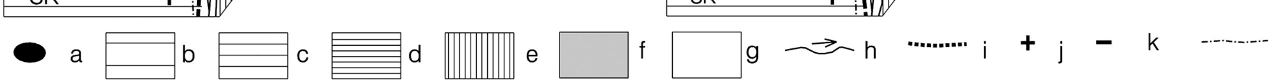


Fig. 7. Bogs in the Orawsko-Nowotarska Basin relative to various age Quaternary glaciofluvial fans and postglacial terraces

Fig. 8. Likely extent of raised bogs in the Orawsko-Nowotarska Basin relative to major landforms prior to anthropogenic degradation

a – preserved fragments of high bogs, remnants of glaciofluvial fans of the following ages: b – Mindel, c – Riss, d – Vistulian, e – postglacial terraces, f – postglacial terraces in valley bottoms, g – areas beyond the borders of the Basin, h – rivers, i – the European Watershed, j – uplifted area, k – downthrusted area, l – state border

Five peat bogs, being in an initial phase of raised peat bog formation, have not changed. The overall size of raised bogs amounted to ca. 4,900 ha and has shrunk by 60% to date. Some raised peat bogs used to be as much as 10 times bigger than their present remnants. The two biggest peat domes stretched over 1,000 ha, while the size of ten domes ranged between 100 ha and 1,000 ha. Many raised bogs were accompanied by circular fringe watercourses. To sum up, it must be concluded that the most extensive raised peat bogs in the Orawsko-Nowotarska Basin were present in the area of the tectonically lowered part of the glaciofluvial fan of the Czarny Dunajec River. Individual raised peat bogs in the Basin used to cover a more morphologically varied area than the current dome remnants and post-peat areas. This indicates an advanced expansion of some raised bogs beyond the location of their primary formation. Thus, when analysing the conditions for the development of individual bogs, account should be taken of the terrain stretching beyond the boundaries of the post-peat areas (Łajczak 2011a, 2013).

Prior to human settlement in the upper San River and the Wołosaty River valleys in the 17th century, the cumulative area of 17 raised bogs amounted to only 62 ha and was only 26% larger than the domes and post-peat areas preserved until the present. In further consideration of the small size of these bogs, they are not presented in graphic form. In this part of the Carpathians, raised bogs did not reach beyond the landforms, which are currently covered by dome remnants and post-peat areas.

Assessment of conditions for peat bog development

The extensive but irregular distribution of raised bogs in the areas in the Polish Carpathians under study was determined by non-climatic characteristics of the terrain. The predominant role in this respect is that of hydrological conditions dependent on the composition of the parent material and land relief. This aspect of the functioning of bogs will be discussed in more detail only with respect to two areas of the Carpathians that are the best explored in this respect: The Orawsko-Nowotarska Basin and valleys in the Bieszczady Mountains. In the second area, the distribution of bogs is strongly determined by neotectonics (Łajczak 2011a, 2013).

Previously, it was argued that climate has a strong and even predominant impact on the development of peat bogs in the Polish Carpathians (Staszic 1815, Zejszner 1848, Hołowkiewicz 1881, Gustawicz 1883, Rehman 1895, 1912, Niezabitowski-Lubicz 1922, Szafer 1928, Korczyńska 1952, Mirska 1956, Koczur 1996, Lipka 1999). On mountain ridges and in mountain valleys located at high altitudes, despite precipitation highly exceeding evaporation in the vegetation growth season, peat bogs develop, as is shown above, only in some morphological situations, with stable although often low-intensity groundwater outflows permanently humidifying gently inclined lower slopes, which are a habitat for hydrophilic vegetation. The role of the parent material is dominant in the development of bogs. It is particularly clear in the Orawsko-Nowotarska Basin, where, according to Kowanetz (1998), the excess of precipitation over evaporation in the vegetation growth season does not exceed 22%, with possible water deficits in August and September. The forms of glaciofluvial and fluvial accumulation in the Orawsko-Nowotarska Basin and in the Bieszczady valleys where raised bogs developed are built of gravels overlain by a ca. 2 m-thick layer of clay with at least 50% loam. The layer of clay was accumulated on glaciofluvial fans as a result of aeolian accumulation, on alluvial fans as a result of washing-away, and on river terraces as a result of accumulation during floods when the channels or watercourses were shallower than currently. The permeability of the layer of clay ranges between "very poor" and "impermeable", while that of gravels is "very good" (Łajczak 2009). The layer of clay on the abovementioned accumulation forms is continuous and it is only on alluvial fans and on the edges of Quaternary terraces that the continuity is interrupted, also under the peat cover.

The layer of clays hinders infiltration by precipitation and melt water, which – considering the gentle slopes (not exceeding 10‰ over almost the entire area) – leads to long-term saturation of the sub-surface layer of soil with water, and creates local overflows and marshes. The first water table occurs in gravels, often directly underneath the layer of clay, which hinders water outflows to the surface over most of the area. Groundwater in glaciofluvial fans and alluvial fans is under slight hydrostatic stress and flows out onto the surface as springs and in particular as seepage in locations where the layer of clay is too thin or is absent. The largest number of outflows of these waters is observed in the lower parts of the fans and in concave landforms within their area. The concave forms include the feet of the scarps of higher terraces, paleochannels, as well as deeper erosive incisions along with source niches. In locations where groundwater outflows neighbour raised bogs or in areas formerly occupied by much more extensive bogs, wetland or boggy hollows have developed. Groundwater outflows are also observed in exhumed paleochannels within post-peat areas.

On the largest glaciofluvial fan in the Orawa-Nowy Targ Basin, i.e. on the Czarny Dunajec River fan, the location of groundwater outflows and consequently of bogs is also determined by tectonic movements. In the western, uplifted part of the fan, which is dissected linearly to a depth of 40 m, peat bogs are not numerous. In turn, in the lower section of the fan, which has the shallowest groundwater table, the number and size of bogs are the greatest. This part of the fan, along the paleochannels of the Czarny Dunajec River and within the area referred to as "Bory Wylewisko" (Flooded Forests), where the number of groundwater outflows is the greatest, used to have the largest raised bogs in the Orawsko-Nowotarska Basin.

Damp depressions with groundwater outflows represent locations where low peat bogs have developed. Given the fact that they are fed by shallow groundwater, and in some situations also by floods from watercourses, peat bogs have not been influenced by climate. The horizontal expansion of these peat bogs reaches as far as the land with a stable high humidity is found, including hydrogenic habitats not undergoing the peat-forming process. After a thick layer of low peat bog has built up, the feeding of which exclusively from the mineral substratum became increasingly difficult, the role of rainwater in further peat bog formation gained in importance. The expanding domes of raised bogs reshaped the local relief, local watershedes and watercourses with shallow channels. After some time, a stable system of fringe flows and transit flows with deeper channels was formed.

Development of raised bogs in different geomorphological situations

The first stage in the development of the peat bogs under study is the creation of a low bog. It was only in raised bogs located on watersheds that the first stage of bog development took place on convex landforms, while the remaining raised bogs started to develop in concave forms or on evenly inclined terrain. In the Polish Carpathians, as exemplified by the Orawsko-Nowotarska Basin and valleys in the Bieszczady Mountains, eight geomorphological situations were distinguished in which expanding raised bogs changed the land relief on a local scale. The locations featuring the groups of bogs that have been distinguished are discussed in order from those lying on the highest ground to those lowest bogs lying in valley and basin bottoms. The following situations are distinguished in terms of the pattern of bog development (Fig. 9).

- I watershed bogs (initially soligenous bogs and then, once the dome starts to build up, ombrogenous bogs),
- II bogs in spring niches of shallow erosion-induced incisions, in the bottom of these incisions and on their slopes (initially soligenous or fluviogenous bogs transformed into ombrogenous bogs),
- III bogs in paleochannels (initially fluviogenous bogs transformed into topogenous and soligenous bogs, and ultimately into ombrogenous bogs),
- IV bogs on high various-age terraces near the base of a higher terrace (initially soligenous bogs, later fluviogenous bogs transformed into ombrogenous bogs),
- V bogs on evenly inclined fragments of the Vistulian terrace in spots with numerous groundwater outflows (initially fluviogenous bogs transformed into ombrogenous bogs),
- VI bogs fully developed on an alluvial fan (soligenous bogs transformed into ombrogenous bogs),
- VII bogs on the edges of single or neighbouring alluvial fans (soligenous bogs transformed into ombrogenous bogs),
- VIII bogs on the post-glacial terrace between an inactive levee and undercut flysch slope, locally at former oxbows (initially fluviogenous or soligenous bogs transformed into ombrogenous bogs)

The development of bogs in situations I, V and VI leads to a gradual local increase in the terrain height difference. In the other situations, as the low bog develops, the terrain levels out, and then, as the peat dome builds up, local height differences increase. Thus, hollow forms in the mineral substratum of the bogs are replaced by convex forms made of peat. The most significant changes in the relief occur in situation III, where an extensive peat dome may even grow on top of several fossilised channels of former neighbouring watercourses. In such a situation, local watersheds shift. In nearly all the above situations, it was found that the buildup of a layer of ombrogenic peat is mainly directed towards areas that are lower in altitude than the location where the bog started to develop. The predominant direction of bog expansion depends on groundwater seepage, which is greatest at sites located topographically below the peat dome.

Pattern of changes in surface drainage as a result of peat bog development

The filling in of terrain depressions with low peat and the subsequent horizontal expansion of peat domes leads to the following surface drainage changes.

1. As early as in the shallow bog development phase, gradual changes in surface drainage begin. Oxbows disappear.
2. As the peat dome expands, fringe flows are formed. At this stage of bog development, the local surface drainage system undergoes the strongest reorganisation, which consists of the fossilisation of watercourse channels and relocation of other watercourse channels. Along with the expansion of peat domes, the area with the thickest peat layer expands ever lower, causing fringe flows to move in that direction at a fast pace.
3. There are transit watercourses at different distances outside the bogs. Considering their size, these flows mark the boundaries of bog expansion,
4. The fringe zones of most of the bogs under study moved closer to the channels of transit watercourses.

Discussion and conclusions

By analysing the relief of raised bogs in the Polish Carpathians some of the characteristics of bogs were examined which had not been previously addressed. Considering the geomorphological criteria for their occurrence, all the bogs examined (Ilnicki 2002) are of the valley type, although they developed within different mesoforms. Raised bogs in the areas under investigation do not solely occur, as claimed by other authors (Tobolski 2000, Ilnicki 2002), on clearly visible watersheds, but mainly in locations that are topographically lower than these. Raised bogs with an extensive dome may develop across the range of altitudes of the areas under study, yet hollow landforms, such as spring niches, paleochan-

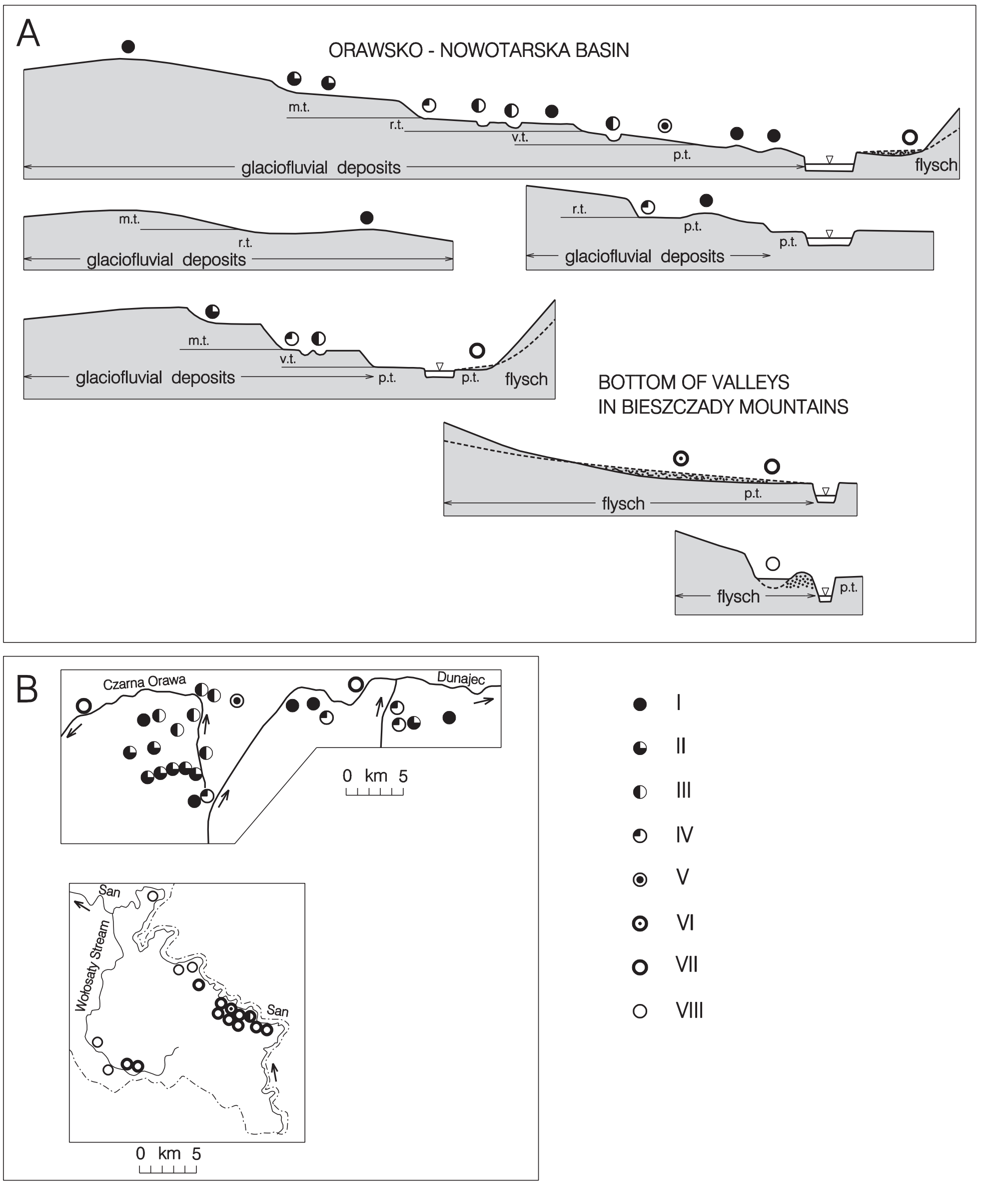


Fig. 9. Geomorphological location of the raised bog groups distinguished in the Orawsko-Nowotarska Basin and in the Bieszczady Mountains

A – altitude profile, B – plan, I–VIII – see in the text, terraces: m.t. – Mindel, r.t. – Riss, v.t. – Vistulian, p.t. – postglacial

nels, scarp bases of higher terraces and alluvial fan edges are favoured in this respect. Stable outflows of shallow groundwater, which are the most intensive in such places, guarantee the development of low bogs, and then, as raised bogs expand, they keep the fringe area highly humidified (Łajczak 2007, 2009).

Although local watersheds run across the bog domes examined, their mineral substratum indicates that they started to develop within hollow landforms. Only a few raised bogs cover convex landforms and according to the classification by Dembek *et al.* (2000) are ombrogenous. In view of the classification by Kaule and Göttlich (1976), this group of bogs are of the ridge type. The remaining, most numerous, bogs have various geomorphological locations and their development was determined to the greatest extent by local land relief and hydrological conditions. According to the classification of Dembek *et al.* (2000) such dome bogs may be classified as raised symmetrical or asymmetrical bogs, and according to the classification of Kaule and Göttlich (1976), as hanging (soligenous) or topogenous bogs. This group of bogs is of the seepage (transit) type and develops at locations with outflows of shallow groundwater. Therefore according to Kaule and Göttlich (1976), they are referred to as ombro-soligenous. According to the classification of soligenous bogs in Poland according to Dembek *et al.* (2000), soligenous bogs on glaciofluvial and alluvial fans in the Orawsko-Nowotarska Basin and in the Bieszczady Mountains may be considered as a transitory type between seepage bogs and pressure bogs.

The figure showing the location of ombrogenous, topogenous, soligenous and limnogenous/fluviogenous bogs in the watershed area, on the slope and on the valley bottom within the lowland area of Poland (Żurek, Tomaszewicz 1996, Ilnicki 2002, Dembek *et al.* 2000) does not reflect the actual variety of bogs in the Orawsko-Nowotarska Basin and the Bieszczady Mountains (Fig. 10). In the areas of the Polish Carpathians under investigation, the distribution of the abovementioned four groups of raised bogs was more complicated in the different stages of their development, which is due to the great diversity of land relief. At present, nearly all raised bogs in these areas are ombrogenous in nature, but since the beginning of their development they have gone through the soligenous and fluviogenous phases. Only the bogs developed over extensive paleochannels on the glaciofluvial fan of the Czarny Dunajec River in the Orawsko-Nowotarska Basin passed through the topogenous bog phase. They can be compared to topogenous bogs over extensive outwash fans over young-glacial areas in northern Poland (cf. Ilnicki 2002). Only some bogs in the initial phase of raised bog formation are still water-fed in a manner typical for soligenous and fluviogenous bogs. The fringe zones of all raised bogs having a non-watershed location are additionally fed by outflows of shallow groundwater. The complex feeding system is most typical of bogs located in depressions surrounding springs, at the scarp base of the higher terrace, at the base of the undercut slope and on the edges of alluvial fans. Kaule and Göttlich (1976) refer to raised bogs fed both by rain and groundwater as ombro-soligenous bogs.

The raised bog feeding regimen changes as its dome expands, when the initially soligenous or fluviogenous bogs transform into the ultimate ombrogenous bogs. As many as half of the bogs within the areas investigated have transformed from soligenous to ombrogenous bogs. This was the case with the following geomorphological groups of bogs: I, IV, VI and VII. Nearly four times fewer bogs transformed from soligenous, through fluviogenous, to ombrogenous bogs (bog groups II, IV, V). The same number of bogs went through an even more complex and long-lasting transformation from fluviogenous, through topogenous, and further on through soligenous to ombrogenous bogs (group III bogs). Four bogs changed from fluviogenous, through soligenous, to ombrogenous ones (group VIII bogs). Three bogs are in a less advanced stage of development, having changed from soligenous to fluviogenous (group II bogs), with two bogs still being soligenous (group II bogs).

The floor of the paludification bogs investigated feature a regular peat layer, which often fills fossil land depressions, with a layer of raised peat atop, mainly the sphagnum bog of which the dome is built. The composition of these bogs corresponds to the pattern proposed by Gore (1983), as well as Obidowicz and Margielewski (2008). In the largest bog domes, which have developed over several neighbouring paleochannels, lower peat is accumulated in separated zones, with the thickest layer of overlaying higher peat not necessarily found over the deepest fossil paleochannel (Baumgart-Kotarba 1991–92). The zone with the thickest peat in the dome, which marks the local water course, shifts as the bog expands and may cover paleochannels. The average thickness of peat in the domes of the bogs examined is 3–5 m and exceeds the average thickness of the deposit in Poland's raised bogs. Only 7% of Polish bogs have such a thick peat deposit and the area they occupy represents 5% of the bogland area (Ilnicki 2002).

The formation of raised bogs, not only in the initial phase of their growth, but also during the growth of the dome, is largely determined by the system of watercourses, which transform with time into fringe watercourses (Łajczak 2006, 2007, 2009). High levels of dampness of the soil in the vicinity of such watercourses fed by the nearby outflows of groundwater guarantee the continuation of the peat-forming process in the fringe zone, and in the marginal zone of the peat domes, which is a prerequisite for their further expansion. Examples of a dense system of fringe watercourses in the vicinity of the largest peat domes in the Orawsko-Nowotarska Basin before the initiation of the

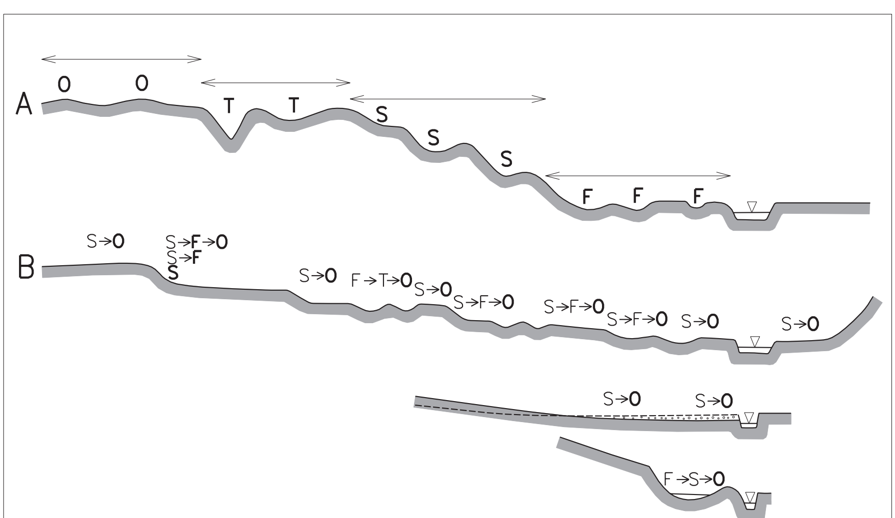


Fig. 10. Location of ombrogenous (O), topogenous (T), soligenous (S) and fluviogenous (F) bogs within areas located between watersheds and valley bottoms in lowland Poland (A) and in the Orawsko-Nowotarska Basin and the Bieszczady valleys (B)
Individual bog development phases are indicated in area B

drainage activity are shown on the map *Karte des Königreisches Galizien und Lodomerien* (1779–82).

Thus, the common belief that raised bogs with well-grown domes in the areas of the Polish Carpathians under study are fed exclusively by rainwater must be questioned, as throughout the development of such bogs, an integral part, i.e. the fringe zone, is largely fed also by groundwater outflows (Łajczak 2007, 2009).

The numerous hydrogenic habitats in the areas under investigation developed on a poorly permeable substratum, often gently sloping, with a stable supply of water from groundwater outflows, do not yet undergo the peat-forming process. Such habitats occur in a wide range of altitudes, also in locations where precipitation is only slightly higher than evaporation in the vegetation growth season. Therefore hydrogenic habitats in the Carpathians represent potential locations for the development of low bogs, which may transform into raised bogs.

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