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# Changes in Raised Bog Relief During the Holocene Case Study: Polish Carpathian Mountains

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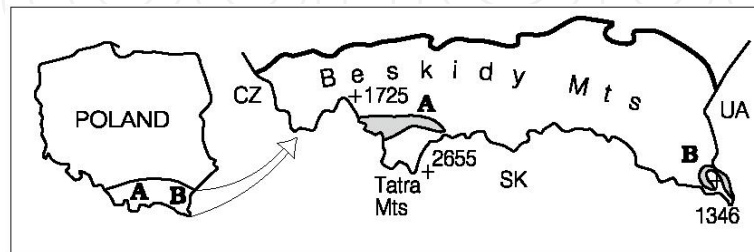
## 1. Introduction

Less attention has been paid to peat bog growth during the Holocene than to contemporary human impact on peat bogs (e.g. Bower 1961, Mallik et al. 1984, Evans 1989, Shaw et al. 1997, Bragg and Tallis 2001, Bindler 2006, Coggins et al. 2006). The research literature states that in order for peat bogs to grow, certain geomorphological, hydrographic, hydrogeological and climate-related conditions must be satisfied (Tołpa 1949, Maksimov 1965, Grosse-Brauckmann 1974, Lowe and Walker 1997, Tobolski 2000, Chairman 2002, Ilnicki 2002). Research studies have identified several types of peat bogs: limnogenous/river-fed, topogenous, soligenous and ombrogenous, all of which differ in terms of relief (Żurek & Tomaszewicz 1996, Tobolski 2000, Ilnicki 2002). In areas with precipitation barely exceeding evaporation, which includes mountain areas, peat bog development is determined by stable groundwater outflows that foster the continuous expansion of hydrogenic sites (Łajczak 2007, 2011). Groundwater outflows create wetlands that foster the development of low bogs. Once low bogs have formed, minerotrophic contact becomes less significant at the bog surface, which leads to oligotrophication and acidification. Both processes then lead to the development of a raised bog (Gore 1983, Tobolski 2000, Ilnicki 2002). The first researcher to note the difference between a low bog and a raised bog as well as their hydrological determinants was Senft (1862).

The greatest geomorphological differences between peat bogs can be observed in the mountains. Peat bogs can be found on ridges, slopes and valley floors (Bower 1961, Kaule and Göttlich 1976, Rawes 1983, Obidowicz 1985, Carling 1986, Rhodes and Stevenson 1997, Bragg and Tallis 2001, Dykes and Warburton 2007, Łajczak 2007, 2011, Obidowicz and Margielewski 2008). While raised bog relief and extent have not been covered explicitly and extensively in the research literature, certain aspects of bog geomorphology have been covered in paleogeographic research in bog areas and research on peat deposit structure. More papers have focused

on historical and modern-day changes in bog relief in areas affected by human activity. What is more rarely encountered is advanced research on modern-day changes in raised bog relief.

Research on raised bog relief in Poland is actually a little more advanced than that in other parts of the world. This is true of northern Poland, which features a large number of bogs, and the Polish Carpathians, which feature just a few bogs. The most thoroughly investigated raised bogs in the Polish Carpathian Mountains are found in the Orawsko-Nowotarska Basin and in valleys in the Bieszczady Range (Fig. 1).



A- Orawsko-Nowotarska Basin, B- Bieszczady Mountains. Fat line shows the northern limit of the Carpathian Mountains in Poland. CZ- Czech Republic, SK- Slovakia, UA- Ukraine.

**Figure 1.** Location of the study areas in southern Poland.

## 2. State of the research

While raised bogs in mountain areas have been the subject of research in a number of scientific disciplines, the evolution of raised bog geomorphology has not been adequately covered. Geomorphologists tend to focus on the difference between low bogs and raised bogs – especially those with a dome (e.g. Senft 1862, Gore 1983, Tobolski 2000, Ilnicki 2002). Other key areas of interest include raised bog relief with respect to the different varieties of bogs (ombrotrophic, soligenous, topogenous, river-fed) found across ridges, slopes and valley floors (e.g. Kaule and Göttlich 1976, Obidowicz 1985, Żurek and Tomaszewicz 1996, Tobolski 2000, Ilnicki 2002, Łajczak 2007, 2011, Obidowicz and Margielewski 2008). The following papers cover geomorphological bog classification systems for mountain areas: Früh and Schröter (1904), Sjörs (1948), Gams (1958), Barsiegan (1974), Kaule (1974), Kaule and Göttlich (1976), Ringler (1981), Obidowicz (1990), Łajczak (2007, 2011). Additional analysis of various aspects of geomorphological bog development can be found in: Bower (1961), Rawes (1983), Mallik et al. (1984), Evans (1989), Cooper and McCaen (1995), Rhodes and Stevenson (1997), Shaw et al. (1997), Bragg and Tallis (2001), Dykes and Warburton (2007), Łajczak (2007, 2011).

Four Holocene stages of raised bog development were identified for mountain areas (Łajczak 2005, 2007, 2011): (a) low bog growth, (b) peat dome growth, (c) human impact on raised bogs leading to complete deterioration, (d) revitalisation of remaining bog fragments. Each stage is shorter than the previous stage. A geomorphological analysis of peat bogs during each stage of development may be found in Łajczak (2005, 2007, 2011). Papers on human impact on peat

bogs tend to focus on the geomorphological effects of peat extraction, drying and burning as well as the effect of grazing and erosion (e.g. Bower 1961, Rawes 1983, Mallik et al. 1984, Carling 1986, Evans 1989, Cooper and McCann 1995, Shaw et al. 1997, Rhodes and Stevenson 1997, Dykes and Warburton 2007, Łajczak 2007, 2011) but often omit a more detailed analysis of changes in peat bog relief. The issue of raised bog development across valley and basin floors in mountain areas has not been well investigated with respect to local relief and sources of water. In addition, the issue of changes in local relief and surface water drainage patterns resulting from peat dome growth has not been adequately investigated.

The best investigated peat bogs with respect to contemporary changes are those in Great Britain and Ireland, where a lot of attention has been paid to the decline of blanket bogs as a result of sheep grazing, peat burning, new drainage systems and to some extent peat extraction (Bower 1961, Mallik et al. 1984, Evans 1989, Shaw et al. 1997, Bragg and Tallis 2001). Papers on human-induced deterioration of peat bogs often focus on peat erosion and omit the issue of changing bog relief (Cooper and McCann 1995).

The most extensive research on peat bogs in the Polish Carpathians has focused on the Orawsko-Nowotarska Basin and the Bieszczady Range. The first area has been investigated since the early 19<sup>th</sup> century, while the second area since the 1950s. Until the 1980s, peat bog research focused only on bog paleogeography, peat properties and plant cover. The oldest carbon dated samples obtained from the bottom of peat domes range from about 2,000 to 11,000 BP (Ralska-Jasiewiczowa 1972, 1980, 1989, Obidowicz 1990, Haczewski et al. 1998). This indicates that the Holocene development of raised bogs in the two study areas was non-synchronous. Peat deposits vary in thickness (1.2 m to 3.6 m), which suggests they are of variable age. Peat domes also vary in size from 0.2 km to 6.0 km (Lipka 1999, Łajczak 2007). This is especially true in the Orawsko-Nowotarska Basin. The mean rate of vertical growth in raised bogs in the Polish Carpathians is estimated to be 0.4 to 0.6 mm a<sup>-1</sup>. This value range is close to that for other European mountain areas (0.3 to 0.7 mm a<sup>-1</sup>) (Żurek 1987). Low bogs developed first in the study area and filled in local depressions and then developed further into peat domes (Ralska-Jasiewiczowa 1972, 1980, 1989, Horawski et al. 1979, Wójcikiewicz 1979, Haczewski et al. 1998, Kukulak 1998, Lipka 1999, Łajczak 2006, 2007, 2009). Researchers began to address changes in bog relief in the Polish Carpathians in the last 20 years – especially with respect to Holocene evolution (Baumgart-Kotarba 1991-1992, Kukulak 1998, Haczewski et al. 1998, 2007) and human impact (Łajczak 2005, 2006, 2007, 2009, 2011).

### 3. Study area

The number of raised bogs in the Polish Carpathians is small compared to the northern lowlands of Poland featuring young Glacial relief (Żurek 1983, 1987, Dembek et al. 2000, Dembek and Piórkowski 2007). Most peat bogs in the Polish Carpathians are less than 1 hectare in area and only a few are larger than 100 hectares (Łajczak 2007, 2009, 2011). Polish Carpathian peat bogs are often found on ridges and in spring areas, moraine depressions as well as landslide depressions. However, the largest peat bogs in this region are found in the Orawsko-

Nowotarska Basin and in the largest valleys in the Bieszczady Range (Fig. 1). Peat bogs occur at lower elevations in mountain areas atop local drainage divides (ombrogenous bogs) and across slopes (soligenous or hanging bogs). Topogenous and river-fed bogs are found at the lowest elevations (Kukulak 1998, Haczewski et al. 1998, 2007, Margielewski 2006, Dembek and Piórkowski 2007, Łajczak 2007, 2009, 2011, Obidowicz and Margielewski 2008).

The Orawsko-Nowotarska Basin has an area of 600 km<sup>2</sup> and is the only intra-mountain basin in the Carpathian Mountains where raised bogs developed during the Holocene (Łajczak 2007, 2009). The Basin is located between a high mountain massif (Tatras) and the lower Beskidy Mountains and is tilted to the north. Peat bogs in the Basin developed across glaciofluvial fans and high Holocene terraces at elevations ranging from 590 m to 770 m. Bogs in the region are found between 5 m and 40 m over river channels. The mean peat thickness in domes exceeds 1 m and may reach 11 m. Raised bogs cover 5% of the Basin area. Low bogs cover 7% of the Basin area. The total peat bog area in the Basin may have reached 40% prior to human settlement in the Late Middle Ages. As settlers began to extract peat and dry peat areas, peat bogs began to shrink to a current 70 km<sup>2</sup>, which includes dome remnants, post-peat areas and low bogs (Łajczak 2007). The European Drainage Divide runs across the Basin from south to north, separating drainage basins of the Black Sea and the Baltic Sea. The southern and western part of the Basin still experiences upward tectonic shifts, while its remaining area is shifting downward (Vanko 1988, Zuchiewicz 2010).

The bottom of the Upper San Valley and the bottom of the Wołosatka Valley are located at an elevation range of 550 to 700 m and have a total area of 13 km<sup>2</sup>. The density of raised bogs in this region is much higher than that in the Orawsko-Nowotarska Basin. However, peat bogs in the Bieszczady Mountains are smaller and less deteriorated due to less peat extraction and less drying (Łajczak 2011). The remaining peat dome fragments and post-peat areas cover 4% of the valley floors in the study area and may be found on postglacial terraces and alluvial fans at heights at 5 to 8 m above river channels. Mean peat thickness in peat domes does not exceed 3 m. Today, the total area of peat domes, post-peat areas and adjacent low bogs does not exceed 1 km<sup>2</sup> (Łajczak 2011).

The parent material of peat bogs in both study areas is a layer of poorly permeable clay about 2 m thick. The clay is located atop water-bearing gravel. The edge zone of virtually every raised bog is recharged by shallow groundwater outflows. Given that precipitation in the study areas barely exceeds evaporation during the vegetation season, minerotrophic recharge must be considered a key determinant of bog development (Łajczak 2009).

#### **4. Purpose of reserach and materials used**

The purpose of the paper is to show how raised bogs in mountain valleys and basins develop during each of the four stages of bog development and how this affects local relief. The research was performed in two study areas in the Polish Carpathian Mountains (Fig. 1).

The paper is based on an analysis of maps from the last 230 years (Karte des Königreichs..... 1779-1782, Administrative Karte..... 1855, Die Spezialkarte..... 1894, Tactical Map..... 1937,



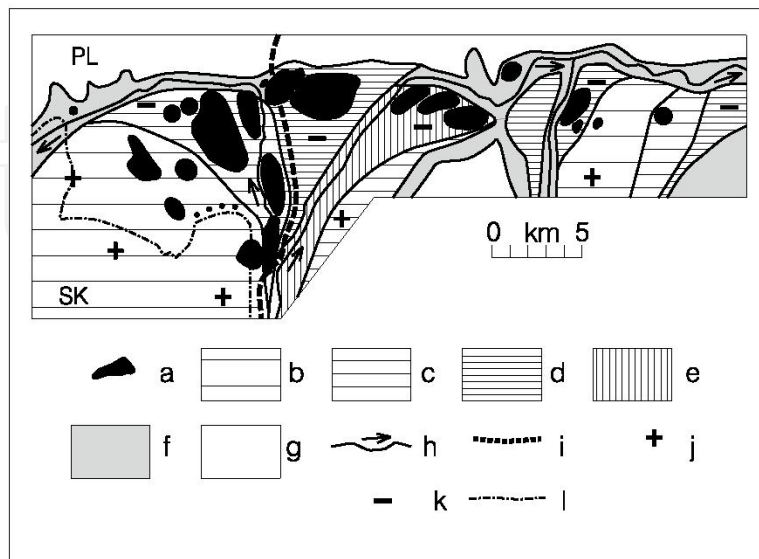
Topographic Maps 1965, 1997) and aerial photographs from 1965, 1988 and 2006. The maps and photographs show the shrinking process for each peat bog analyzed in the study area. In addition, extraction scarps and post-peat areas are analyzed. The paper also employs data obtained via fieldwork, which included peat bog and post-peat area mapping using GPS and morphometric measurements. The research was performed over the course of 15 years in the two study areas mentioned earlier (Łajczak 2007, 2009, 2011). Peat deposit thickness was ascertained via drilling. Maximum peat thickness data were obtained from the research literature (Horawski et al. 1979, Wójcikiewicz 1979, Baumgart-Kotarba 1991-1992, Kukulak 1998, Lipka 1999, Haczewski et al. 2007). Fieldwork focused on the location of peat deposit remnants outside of known peat areas, especially in areas where peat extraction was halted before 1850. This type of information makes it possible to make inferences about the previous extent of peat domes, which were often larger than that shown on the oldest maps (Łajczak 2007, 2009, 2011). The analysis of exhumed landforms in post-peat areas helps to identify places with the thickest peat deposits. Such places are understood to be the original peat formation sites. The research results were used to assess the most likely size of peat domes prior to human impact based on local relief and distribution of water phenomena.

## 5. Results

### 5.1. Reconstruction of raised bog range for the period prior to human impact

The oldest maps analyzed and the traces of peat found outside of contemporary post-peat areas suggest that 26 raised bogs may have existed in the Orawsko-Nowotarska Basin prior to human settlement (Fig. 2). The total area of raised bogs prior to human settlement has been estimated to be about 4,900 ha (Łajczak 2007). Three of the bogs were completely eliminated in the 19<sup>th</sup> century. Eighteen became smaller and some became fragmented. Only five of the bogs have remained in their natural state (Łajczak 2011). The raised bogs of the past covered a more topographically diverse landscape than do their fragments today (Horawski et al. 1979, Wójcikiewicz 1979, Baumgart-Kotarba 1991-1992, Lipka 1999, Łajczak 2007, 2009). This makes it possible to assess how raised bogs at the advanced stage of development are able to alter local relief. The two largest peat domes were most likely 1,000 ha in size. Nine peat domes ranged from 100 ha to 1,000 ha in area. The largest peat domes (dimensions: 5 x 2 km and 4 x 2 km) were some of the largest in modern-day Poland (Łajczak 2007). Transit streams flowing around peat bogs, especially in areas beyond the lowest parts of edge zones had a meandering pattern. The streams were recharged primarily by water seeping out of peat bogs. Raised bogs in the Orawsko-Nowotarska Basin sit atop fragments of Quaternary glaciofluvial fans of variable age. Some are found atop Holocene high terraces (Baumgart-Kotarba 1991-1992, Łajczak 2007, 2009). In general, the younger the fragment of Quaternary glaciofluvial fan, the more expansive the raised bogs used to be. This can be explained in terms of neotectonics, local relief and hydrogeological conditions (Fig. 2). Groundwater flows at greater depths in the western and southern parts of the Basin that are being lifted upward and fragmented by erosion. In turn, this does not favor bog growth. Groundwater in the lower part of the Basin

can be found at shallow depths and groundwater outflows create wet conditions in the area, which in turn favors bog growth (Łajczak 2009).



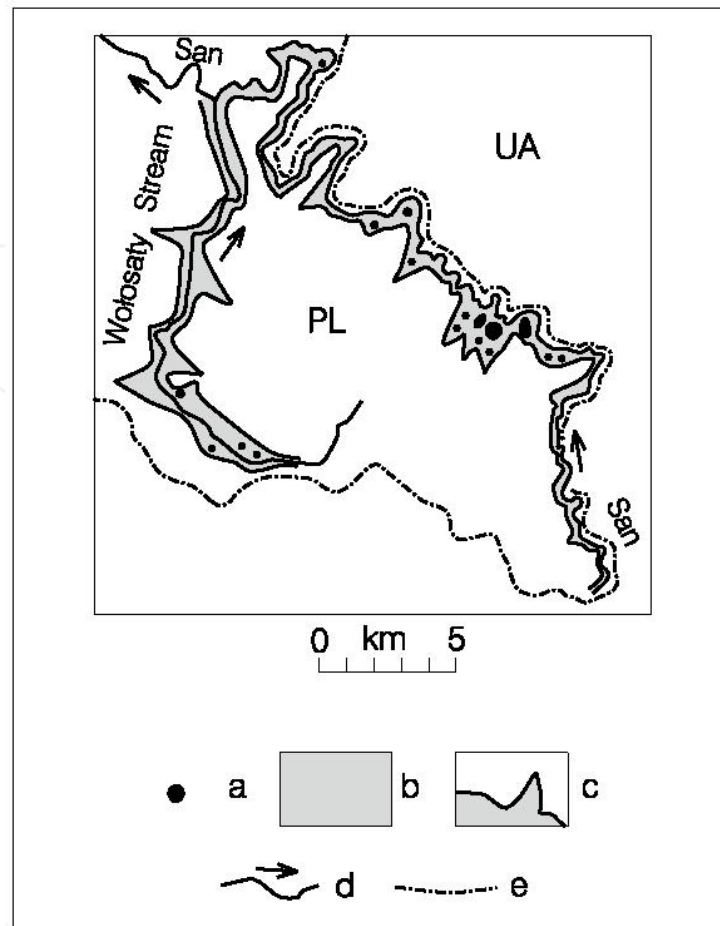
**Figure 2.** Probable range of raised bogs in the Orawsko-Nowotarska Basin in the period prior to human impact. The raised bogs are presented on the background of Quaternary landforms. a- raised bogs. Quaternary terraces within glaciofluvial fans: b- Mindel terraces, c- Riss terraces, d- Vistulian terraces, e- postglacial terraces, f- Holocene terraces. g- areas located outside the basin, h- main water-courses, i- European Drainage Divide, j- areas shifting upward, k- areas shifting downward, l- state border.

Seventeen raised bogs existed in the Upper San Valley and the Wołosatka Valley in the Bieszczady Mountains prior to human settlement in the 17<sup>th</sup> century (Kukulak 1998, Haczewski et al. 2007, Łajczak 2011). The 17 bogs had a total area of only about 60 ha and developed across topographically homogenous terrain – often close to streams – on high terraces and alluvial fans (Fig. 3).

## 5.2. Distribution of peat bogs at different elevations

Eight types of geomorphological situations were identified for raised bogs location at different elevations in the study areas (Fig. 4A). Each type of bog is listed starting at high elevations and ending with low elevations. Their spatial distribution within both studied areas is shown in Fig. 4B. In each geomorphological situation, expanding peat bogs alter relief in a different way (stages “a” and “b” in Łajczak 2005, 2007, 2011). This process is perturbed or halted as a result of human impact – stage “c”. While currently almost all of the bogs are classified as ombrogenous or ombrogenous-soligenous using the Kaule and Göttlich (1976) classification system, each group of peat bogs was recharged by water in a variety of ways during its unique development stage.

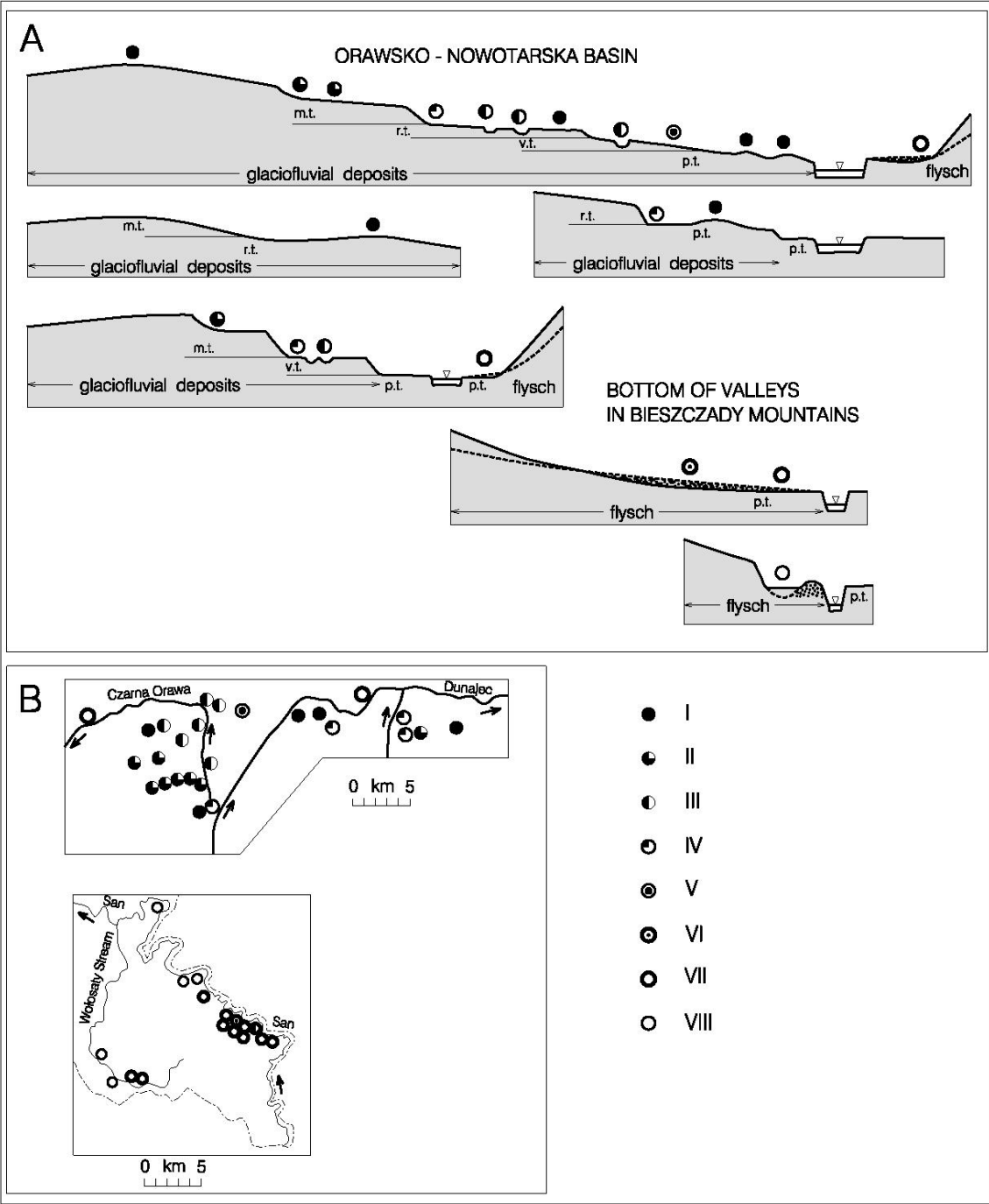
The first group of peat bogs (I) includes five bogs located atop a drainage divide and are found only in the Orawsko-Nowotarska Basin on ridges 5 to 40 m over adjacent surfaces (Baumgart-Kotarba 1991-1992, Lipka 1999, Łajczak 2005, 2007, 2009). Group I bogs were



**Figure 3.** Probable range of raised bogs in bottoms of the Upper San and Wołosatka river valleys in the Bieszczady Mountains. a- raised bogs, b- bottoms of river valleys, c- limit of larger alluvial fans, d- main water-courses, e- state border.

soligenous bogs during the early stage of development. The second group of peat bogs (II) includes eight bogs in spring areas in shallow erosion incisions or at the bottom or on the sides of erosion incisions (Orawsko-Nowotarska Basin) (Łajczak 2007, 2009). Group II bogs were soligenous or river-fed bogs during the early stage of development. The third group of peat bogs (III) includes six bogs in the Orawsko-Nowotarska Basin and one bog in the Bieszczady Mountains. Group III bogs developed in old river channels found on Riss, Vistulian and older Holocene terraces (Baumgart-Kotarba 1991-1992, Kukulak 1998, Łajczak 2005, 2007, 2009, Haczewski et al. 2007). Group III bogs then transformed into river-fed bogs, topogenous bogs, soligenous bogs and finally into ombrogenous bogs. Group IV includes four bogs found on terraces of variable age near the base of the edge of the next higher terrace (Łajczak 2005, 2007). All four are found in the Orawsko-Nowotarska Basin. Group IV bogs were soligenous and later river-fed bogs in the early stage of development. Group V consists of just one bog in the Orawsko-Nowotarska Basin, which had developed on an expansive and uniformly tilted fragment of the Vistulian Terrace. This bog was soligenous at first and then became river-fed. Group VI can be found only in the Bieszczady Mountains and consists of just one bog on an alluvial fan (Łajczak 2011). The bog started





**Figure 4.** Geomorphological location of identified eight groups of raised bogs in the study areas. A- distribution of peat bogs at different elevations, B- their spatial distribution within both areas. For numbering of peat bog groups (I-VIII) – see the text. Terraces: m.t.- Mindel, r.t.- Riss, v.t.- Vistulian, p.t.- postglacial.

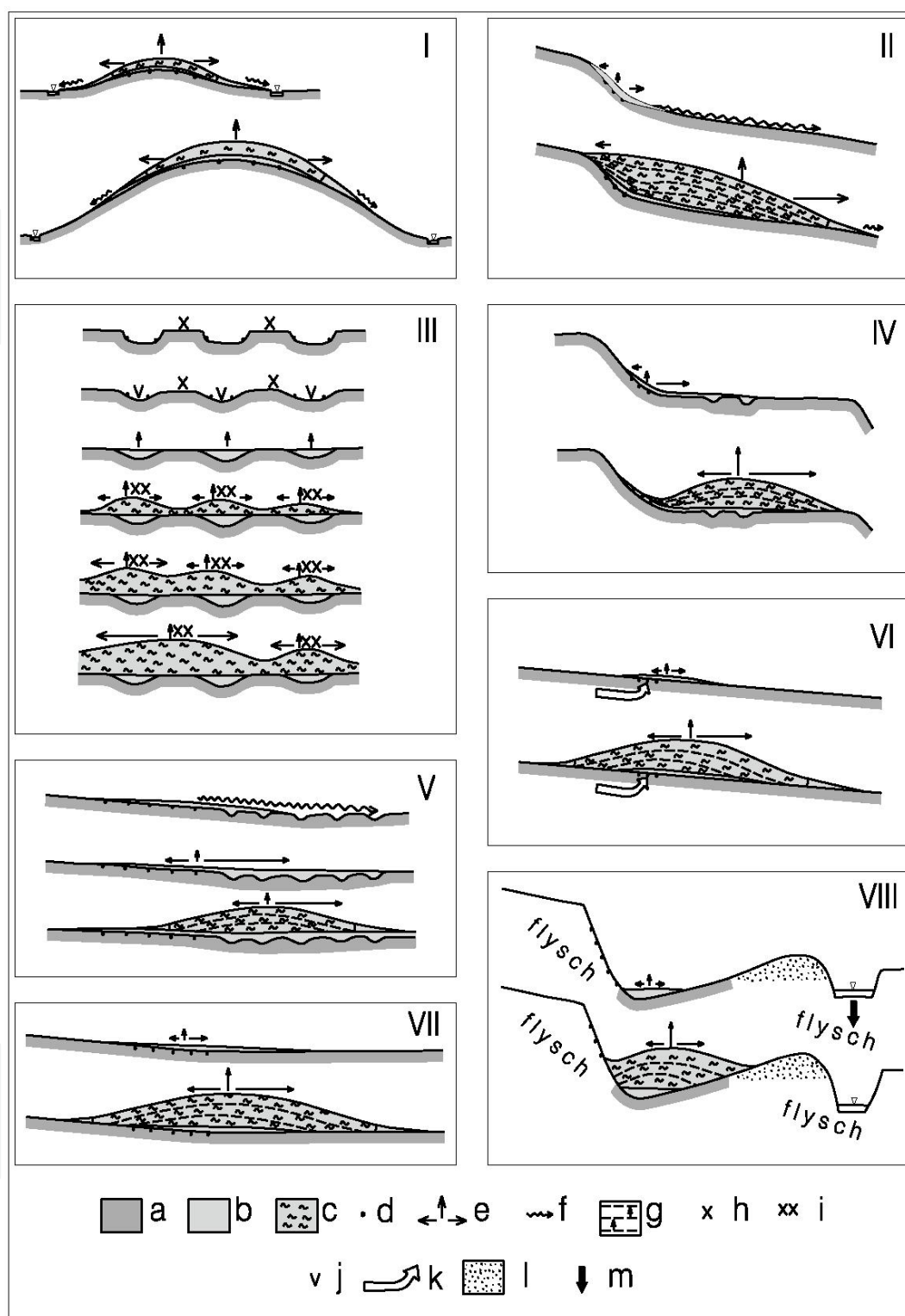
out as a soligenous bog. Group VII is the largest of the groups and includes 12 raised bogs found at the edges of alluvial fans (Łajczak 2009, 2011). Ten of the bogs are found in the Bieszczady Mountains and were initially soligenous. Group VIII is found at the lowest elevations and includes five bogs in the Bieszczady Mountains. The bogs fill in oxbow lakes on the postglacial terrace between an inactive levee and an undercut flysch slope (Kukulak

1998, Haczewski et al. 2007, Łajczak 2011). The bogs were river-fed at first and then remained both ombrogenous and soligenous throughout their period of development.

### 5.3. Changes in peat bog relief during the first stage of development

The first stage of development of the studied bogs consisted of the formation of a low bog. In the case of bogs located atop drainage divides, the first stage of development included convex landforms, while other types of bogs developed in concave landforms (Ralska-Jasiewiczowa 1972, 1980, 1989, Kukulak 1998, Łajczak 2005, 2007, 2011, Haczewski et al. 2007). At this stage of development, bogs in Group I began to evolve in a way that included increasing differences in local elevation. On the other hand, other groups of peat bogs evolved in a completely different manner by reducing differences in local elevation. This process continued until low bogs filled in concave landforms (Fig. 5). This stage was dominated by soligenous bogs, with some river-fed bogs and topogenous bogs. Even bogs growing on convex landforms were initially recharged by shallow groundwater outflows. As the low bog became thicker and its surface farther removed from minerotrophic waters, oligotrophication and acidification of the site began to occur, leading to the development of a raised bog (Ralska-Jasiewiczowa 1989, Kukulak 1998, Łajczak 2005, 2007).

In raised bogs located atop drainage divides (I), the initial stage of development affected the entire cross section of low ridges. Only the tops of higher ridges were affected. Some Group II bogs were hanging bogs during their initial stage of development. This may be inferred from the presence of modern-day hanging bogs in the area that have not yet proceeded to the raised bog stage. Low bogs developed downstream of springs and expanded around them, although the principal direction of expansion remained downstream (Łajczak 2005, 2007, 2009). Low bogs in Group III began to develop after local streams dried up and became filled with fine-grained sediments featuring shallow groundwater. The initial stage of development of Group IV bogs occurred around spring niches at the base of a scarp of an upper terrace as well as in stream channels fed by these same springs during the Holocene. Such sites became collection points for poorly permeable clayey sediments carried in by sheet wash. Further low bog development encompassed ever larger parts of terraces (Łajczak 2005, 2007, 2009). A Group V raised bog began to develop in an area with numerous springs and over time began to cover the downstream parts of stream channels. A Group VI raised bog began to develop in an area with a gap in the poorly permeable layer of clay sitting atop gravel forming the alluvial fan. This type of situation created the right conditions for shallow groundwater to exit the ground under pressure. Group VII bogs located at lower elevations did not form due to river flooding but due to numerous springs at the base of alluvial fans. The development of these low bogs once again led to the accumulation of peat in various concave landforms situated mainly at lower elevations (Łajczak 2005, 2007, 2009). The first stage of bog development (VIII) at lower elevations was accompanied by the last stage of oxbow lake sediment accumulation (Kukulak 1998, Haczewski et al. 2007, Łajczak 2011). At first, the bogs were periodically flooded. However, the bogs were always recharged to some extent by groundwater from an undercut slope located nearby. This remains true today.



**Figure 5.** Scheme of growth of distinguished raised bog groups. For numbering of peat bog groups (I-VIII) – see the text. a- sub-peat material, b- low bog material, c- peat typical for raised bog, d- shallow ground water outflow, e- directions of low bog and raised bog expansion, f- surface water outflow, g- vertical peat dome growth, h- local drainage divide lines in Early Holocene, i- shifted local drainage divide lines, j- dried stream channels and filled with fine-grained sediments, k- places of shallow ground water outflows on alluvial fans, l- levee, m- channel deepening during the Holocene.

#### 5.4. Changes in peat bog relief during the second stage of development

The growth of peat domes across low bogs marks the second stage of bog development, which can be interrupted or halted by human impact. The second stage began at different times for different bogs in the study area. Nevertheless, this stage of development of most bogs started during the Atlantic Period or earlier (Ralska-Jasiewiczowa 1972, 1980, 1989, Obidowicz 1990, Kukulak 1998, Haczewski et al. 2007). The second stage produced much larger changes in relief than the first stage (Łajczak 2005, 2007) (Fig. 5). The key change was fossilization of concave landforms, which became filled in by low bogs and then transitioned into raised bogs. Peat dome growth led to the formation of convex landforms atop formerly concave landforms. Other effects included the shifting of local drainage divides and a marked decrease in the density of local streams flowing close to expansive peat domes. Streams flowing in the vicinity of growing peat domes also changed course. Another tendency in raised bog development is the shift towards lower elevations, which now feature thicker peat deposits. This shift started already at the first stage of development. In effect, the thickest peat deposits are found relatively far away from the original peat formation site (Łajczak 2005). Hence, peat dome development creates increasing differences in local elevation. The opposite trend was found to be true for the first stage of bog development. However, each peat bog is different and may exhibit unique changes in relief development.

Growing peat domes covered the tops and sides of ridges found on drainage divides and their edge zones approached nearby stream channels. Higher ridges became covered by peat domes only at the top, while dome edge zones covered the upper parts of gentle slopes. The thickest peat deposits – formerly more than 6 m thick and currently up to 4 m thick – formed atop a drainage divide (Lipka 1999, Łajczak 2005, 2007). As peat domes continued to grow, so did local differences in elevation. In places with low bogs filling spring niches, growing peat domes filled in erosion incisions and created small hills in some places. As peat domes grew, their thickest deposits were to be found downslope. In such cases, the edge zone covered shallow depressions between domes and higher sections of mineral parent material. These areas are recharged by groundwater outflows and possess edge streams and larger transit streams as well. The development of raised bogs in this area also leads to larger local differences in elevation. The path of development for raised bogs in old stream channels was similar. Growing peat domes covered even neighboring erosion incisions and often joined other peat domes to form expansive domes that mask the morphologically diverse parent surface (Baumgart-Kotarba 1991-1992, Łajczak 2007). The thickest peat deposits (up to 11 m) were found at locations where the dome peaks sit atop the deepest old stream channels. In the fourth group of bogs found on high terraces at the base of the edges of even higher terraces, peat domes developed far away from groundwater outflows and cover old stream channels of a rather small size. At these sites, the peat thickness exceeds 6 m. The development of the Group V peat bog followed a similar path. Maps from 1779-1782 and 1855 show that it used to be surrounded by a wide swath of low bogs. Edge streams and larger transit streams beyond the low bogs followed a meandering course. The expansion of raised bog on the alluvial fan was limited by the presence of larger transit streams. On the other hand, the expansion of peat bogs across the lowest parts of the alluvial fans was not limited by any topographic barriers. The

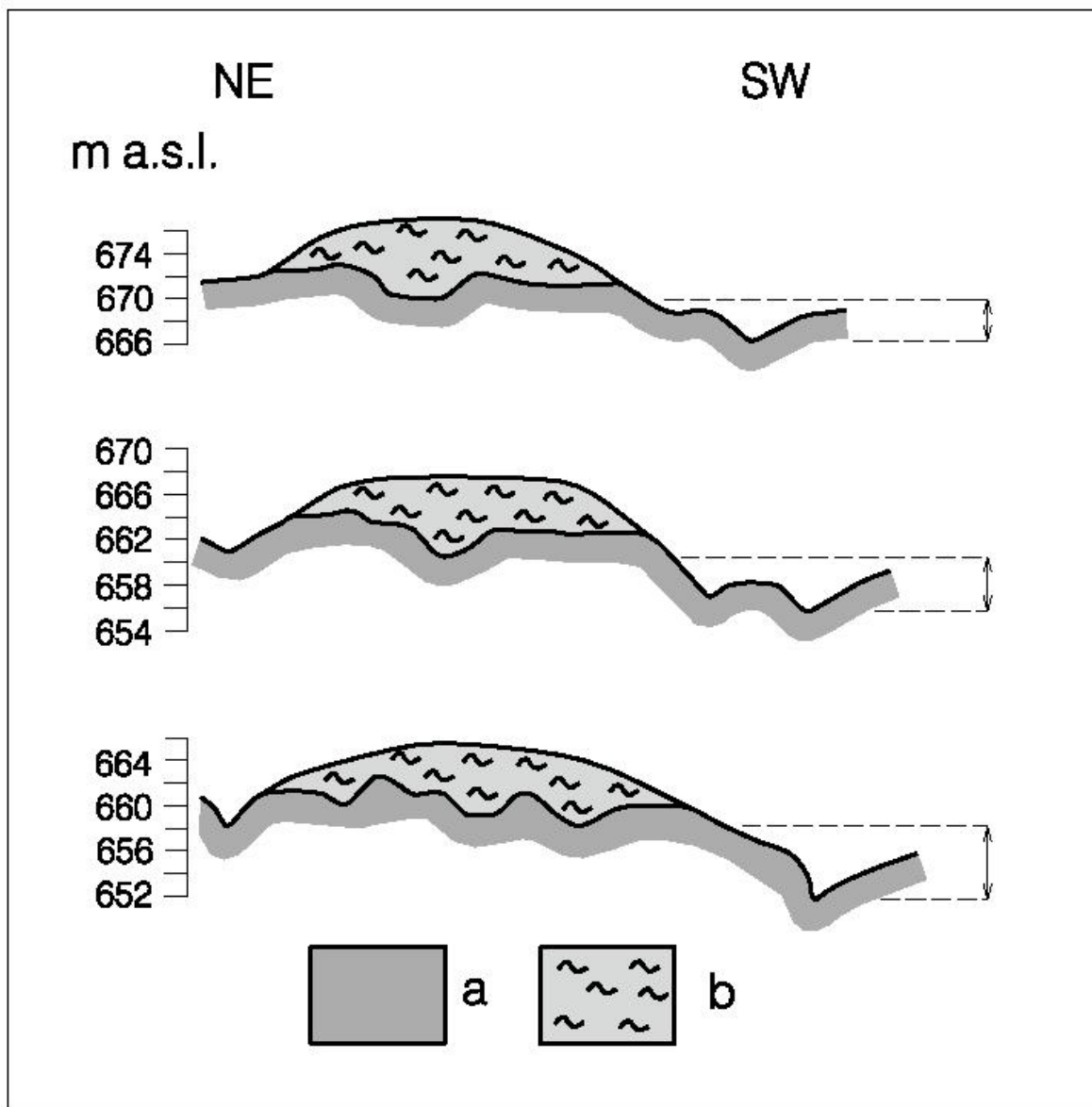
growth of the peat dome tends to smooth out the local land surface up to a certain point – peat deposit 5 m thick or more – at which it leads to increasing local differences in elevation. The development of peat domes in the group located at the lowest elevations also leads to increasing local differences in elevation (Kukulak 1998, Haczewski et al. 2007, Łajczak 2011). This group of raised bogs has already reached its maximum extent, as its edge zone runs along the foot of an undercut slope and a levee on the other side.

Growing peat bogs may strongly affect the network of local stream channels. The development of low bogs can affect the course of small streams. Peat also fills in oxbow lakes. At the advanced stage of raised bog development, the stream network becomes substantially reorganized. Peat domes cover some stream channels and some streams are forced to shift away from the dome (Łajczak 2007). Such streams become edge streams flowing around the peat dome. These streams are narrow and cut relatively deep into peat deposits in many cases. As peat domes expand, the thickest peat deposits tend to be found at increasingly lower elevations. This forces edge streams to quickly shift downslope. Larger transit streams are found beyond the edge zone of the peat dome and may limit dome expansion depending on their size. These streams and edge streams were recharged prior to human impact by numerous short tributaries seeping out of peat domes and flowing across the muddy edge zone. In the study area, the edge zones of many bogs approached small streams but remained 300 m or more away from larger rivers. Streams of varying size flowing outside of the peat edge zone, especially at lower elevations, tend to meander. The channels of transit streams flowing near the largest peat bog in the Orawsko-Nowotarska Basin are as much as six meters lower than the old stream channels masked by the expansive peat dome (Baumgart-Kotarba 1991-1992) (Fig. 6). This suggests that these large streams became much deeper during the Holocene in the absence of peat formation.

### 5.5. Human impact on peat bog relief

Prior to the introduction of agriculture in the Orawsko-Nowotarska Basin towards the end of the Middle Ages, raised bogs most likely occupied about 10% of the Basin, while low bogs may have occupied as much as 30% of the Basin. In the valleys studied in the Bieszczady Mountains, the numbers were closer to 6% and 4% (Łajczak 2007, 2011). Some fragments of the two study areas were already largely covered by peat bogs (Figs 2, 3). In the Orawsko-Nowotarska Basin, incoming settlers began to clear low bogs by burning the peat. In the 18<sup>th</sup> century, peat extraction began at the edges of peat domes. The peat was used to heat homes. Peat extraction intensified between the mid-19<sup>th</sup> century and the late 20<sup>th</sup> century. Peat extraction usually started at the edge of the dome and continued towards the center and normally did not involve the entire dome all at once. Peat dome burning continued until the early 1900s. In the 1950s, industrial-scale peat extraction began at three peat bogs in order to serve the gardening needs of Polish consumers. Drainage work began at the same time around the edges of peat bogs and stream channels became regulated, which led to the drying of large parts of the bogs. This caused a more than three-fold reduction in the low bogs' total area. Raised bogs became reduced 60% (Łajczak 2007, 2011) (Fig. 7). Human impact began to reduce the extent of raised bogs in the Bieszczady Mountains starting in the 19<sup>th</sup> century. The reductions ended in the

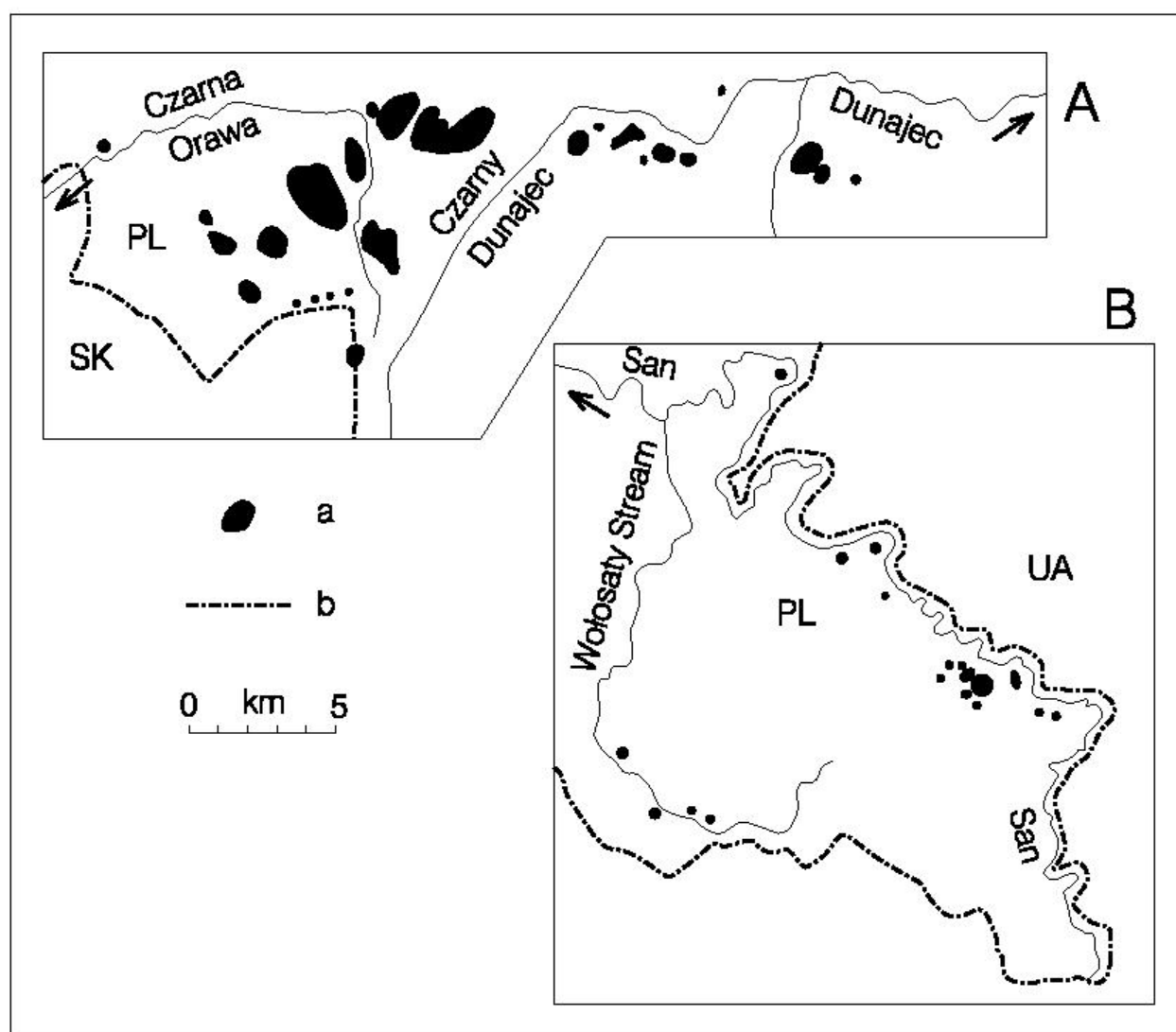




**Figure 6.** Chosen cross-sections through the largest raised bog in the Orawsko-Nowotarska Basin. a- sub-peat material, b- peat deposit. Differences between elevation of fossilized channels and active stream channels are marked.

1950s. The edges of these bogs were later dried (Łajczak 2011). Today peat bogs in the valleys of the Bieszczady Mountains are protected by law, which makes bog revitalisation possible. Only one large bog in the Orawsko-Nowotarska Basin is protected by law. Almost all others are no longer experiencing human impact and are slowly regenerating.

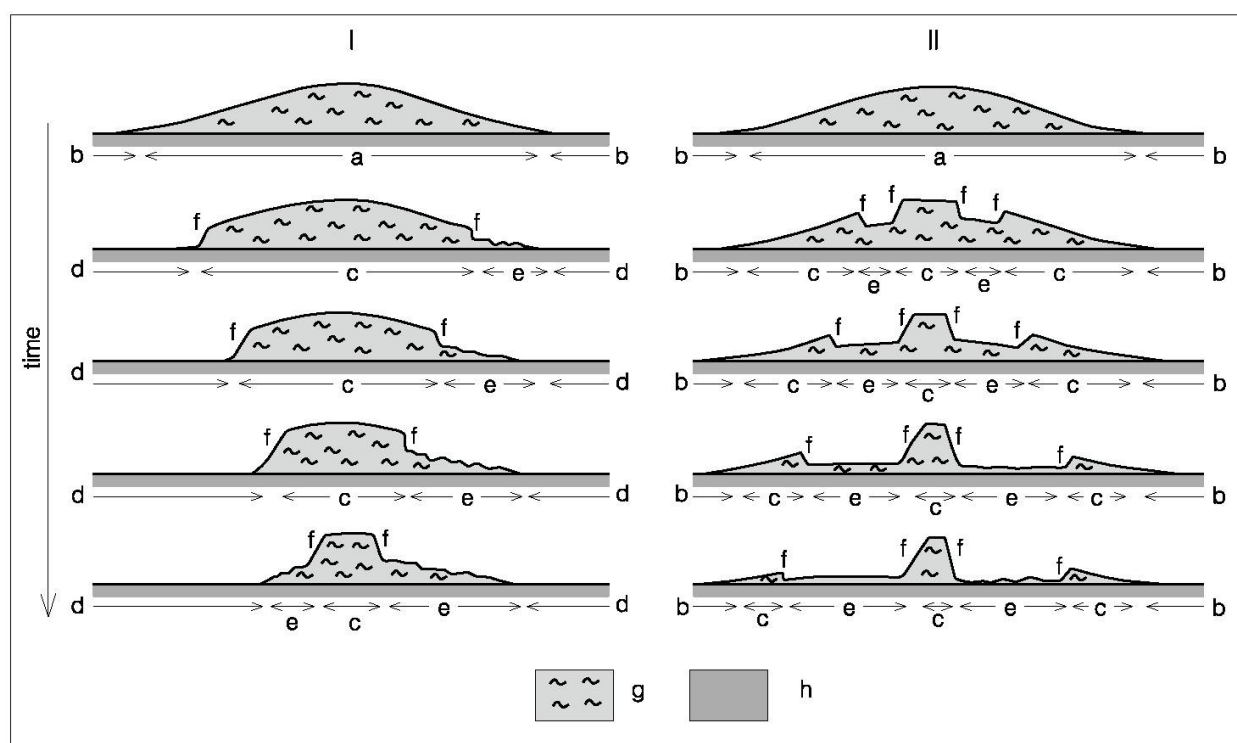
Human impact on raised bogs helps create the following landforms: 1) shallow hollows after the surface layer of a peat dome has been burned off or after the entire peat deposit in a low bog has been burned off, 2) peat extraction pits of varying size and shape, 3) drainage ditches, 4) regulated and/or straightened stream channels (e.g. Rawes 1983, Mallik et al. 1984, Evans 1989, Cooper and McCaan 1995, Rhodes and Stevenson 1997, Shaw et al. 1997, Bragg and Tallis 2001, Łajczak 2007, 2011, Latocha 2012). Peat extraction alters bog relief in the most visible of



**Figure 7.** Actual range of remnants of peat domes in the study areas. a- remnants of peat domes, b- state border.

ways (Fig. 8). Extraction from the edges towards the center of the dome produces one type of bog relief, while the opposite direction of extraction produces another type of bog relief. Peat extraction leads to the fragmentation of some peat domes. One dome in the Orawsko-Nowotarska Basin has broken up into three fragments (Łajczaka 2011).

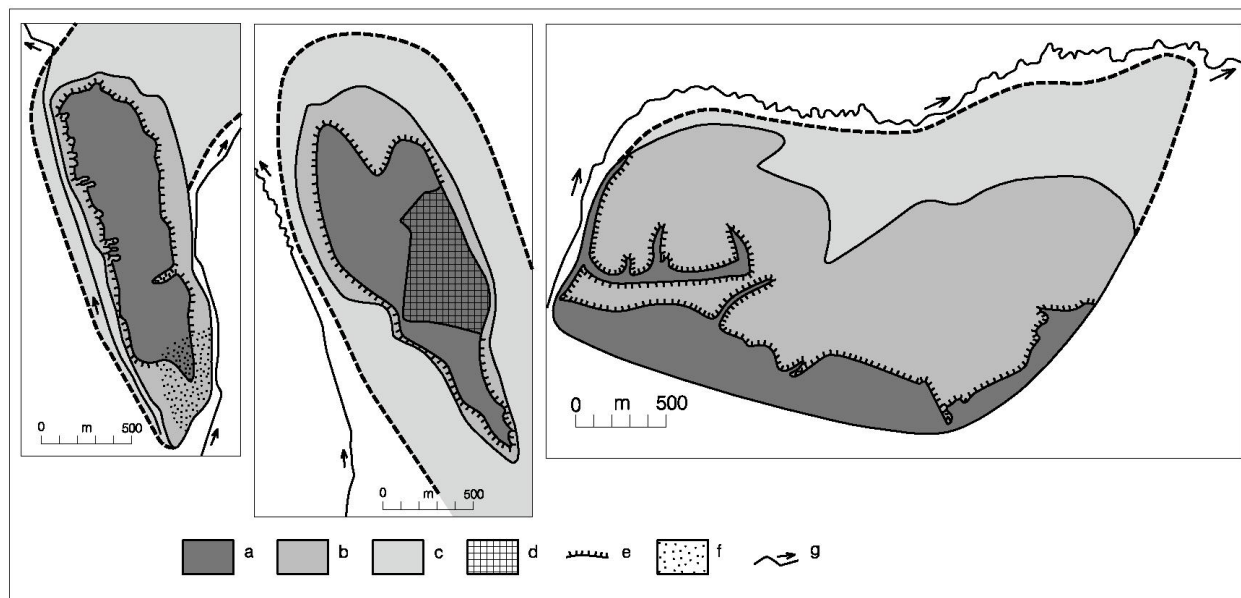
In areas where peat extraction had been taking place for very many years, the following landforms can be observed: 1) older post-peat areas with occasional traces of peat that are used for agricultural purposes, 2) younger post-peat areas with reduced but continuous peat deposits, 3) peat domes reduced to peat remnants, 4) active industrial-scale extraction areas that yield large depressions atop peat domes that usually link with younger post-peat areas, 5) extraction scarps or post-extraction scarps that separate peat dome remnants from younger post-peat areas as well as expansive depressions atop peat domes (Łajczak 2011). In the Orawsko-Nowotarska Basin, older post-peat areas formed not later than the mid-19<sup>th</sup> century and mark areas previously occupied by low bogs, edge fragments of raised bogs and three



**Figure 8.** A schematic diagram illustrating the decrease of the range of peat dome as a result of peat extraction. I- peat extraction from the edge towards the center of the dome, II- opposite direction of peat extraction. a- peat dome, b- low bog, c- remnant of peat dome, d- older post-peat area, e- younger post-peat area, f- extraction scarp or post-extraction scarp, g- peat deposit, h- sub-peat material.

entirely destroyed raised bogs. There are no older post-peat areas in the Bieszczady Mountains. Older post-peat areas feature exposed mineral parent material where landforms can be observed that served as potential starting points for peat formation (Łajczak 2006). In younger post-peat areas, the reduced peat layer features a diverse surface with numerous low scarps, pits filled with water and peat deposits overgrown with moss. Younger post-peat areas occupy a much larger area in the Orawsko-Nowotarska Basin than in the Bieszczady Mountains. In the Orawsko-Nowotarska Basin, younger post-peat areas are surrounded by wide older post-peat areas. Existing fragments of peat domes possess virtually fully natural tops and are surrounded by extraction scarps or post-extraction scarps. The scarps can be as high as 6 m and are either fully vertical or stair-shaped. In bogs where most of the peat has been extracted, reduced peat domes take the form of narrow peat remnants. In the Orawsko-Nowotarska Basin, peat dome remnants are much smaller than the original domes. However, in the Bieszczady Mountains, peat dome remnants are only slightly smaller than the original domes (Łajczak 2011). Expansive depressions found atop peat domes have formed only in three peat bogs in the Orawsko-Nowotarska Basin. The depressions occupy no more than 20% of the existing domes' surface and can be as deep as 4 m. Each depression is ringed by vertical scarps and drained by a dense network of drainage ditches (Łajczak 2007, 2011). In the Orawsko-Nowotarska Basin, scarps surrounding peat remnants tend to zigzag, while in the Bieszczady Mountains, the scarp geometry is either bent or circular. In most of the investigated peat bogs where peat extraction had proceeded from the edge towards the center of the peat dome, the

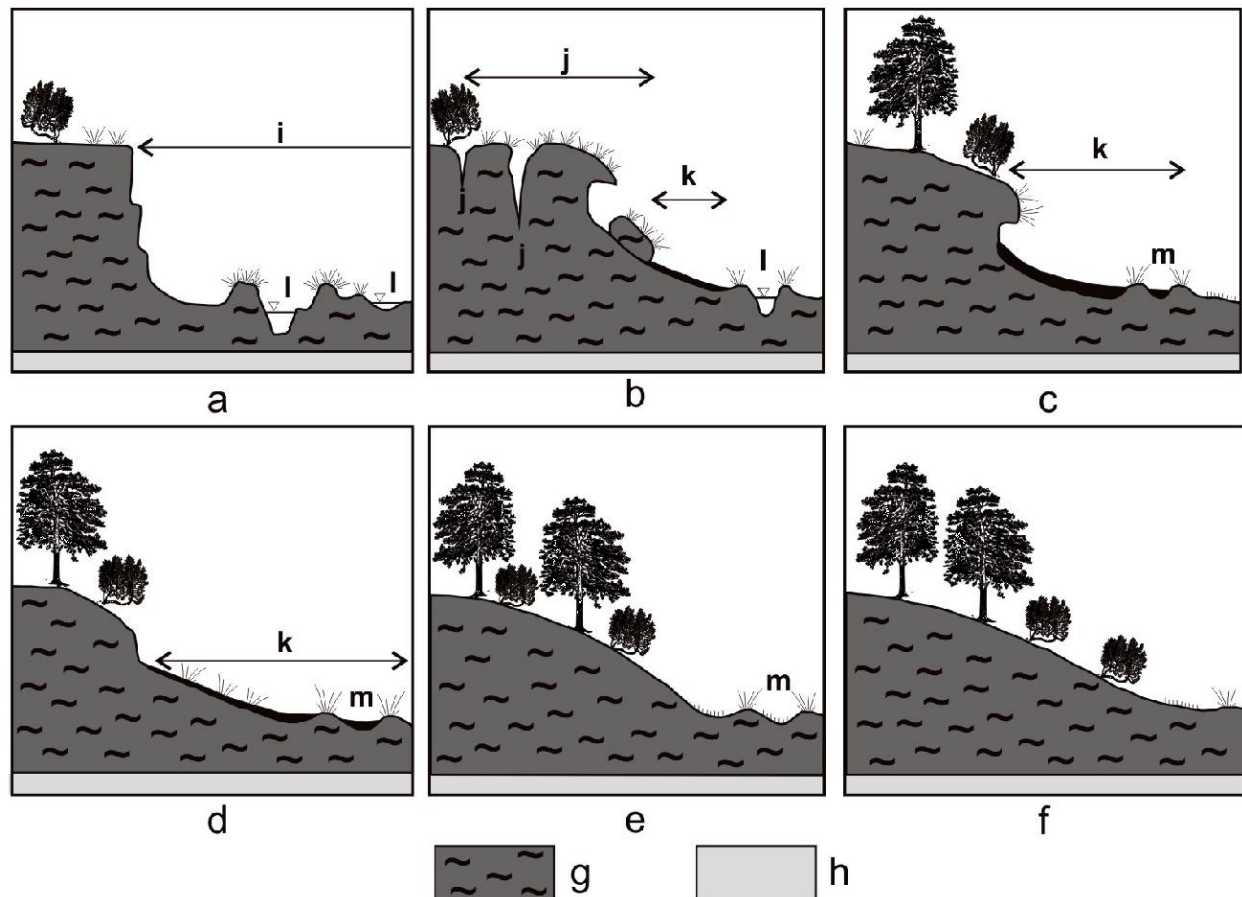
aforementioned elements of the morphology of damaged raised bogs tend to form a circular pattern around the peat dome remnants. In peat bogs where peat extraction had proceeded all over the place, the circular pattern does not exist (Fig. 9).



**Figure 9.** Distribution of main morphological elements within former large raised bogs – examples from the Orawsko-Nowotarska Basin. a- remnant of peat dome, b- younger post-peat area, c- older post-peat area, d- industrial-scale extraction area that yields large depression atop peat dome, e- extraction scarp or post-extraction scarp, f- part of a bog which has preserved natural character, g- main water-courses.

The most visible and most rapidly changing elements of relief in bogs affected by human impact are extraction scarps (Łajczak 2007, 2011, Latocha 2012). The edges of drained areas are also surrounded by scarps but they are lower. The depressed surface with dried peat is often separated from peat saturated with water by a large ditch. When peat extraction comes to an end, the post-extraction scarp changes along its vertical axis, as illustrated over time by Figure 10. The drying of peat on initially vertical walls of the scarp leads to fractures in the peat deposit and to peat sliding downward where it is washed away during snow melting periods, mainly. Peat mud fills numerous pits in younger post-peat areas. Peat hanging over the declining scarp deteriorates over time and the scarp becomes flat. A fully overgrown former scarp assumes a convex-concave shape with a small gradient. This shape becomes even smoother over time as extraction pits become overgrown and new deposits form. Cartographic materials, old photographs, and the opinions of persons involved in peat extraction indicate that post-extraction scarps maintained their vertical walls for ten years after extraction ceased in the Orawsko-Nowotarska Basin. The more time passes since the end of peat extraction, the more a post-extraction scarp resembles a mature scarp. Phase “c” scarp is about twenty years older than phase “b” and phase “d” scarp is between 30 and 60 years old. Scarps in existence more than 60 years since the end of peat extraction are designated “e” or “f”. A mature convex-concave peat dome cross section can be found only in the case of one peat dome in the Orawsko-Nowotarska Basin. This peat dome has been protected by law since the 1920s (Łajczak 2006).

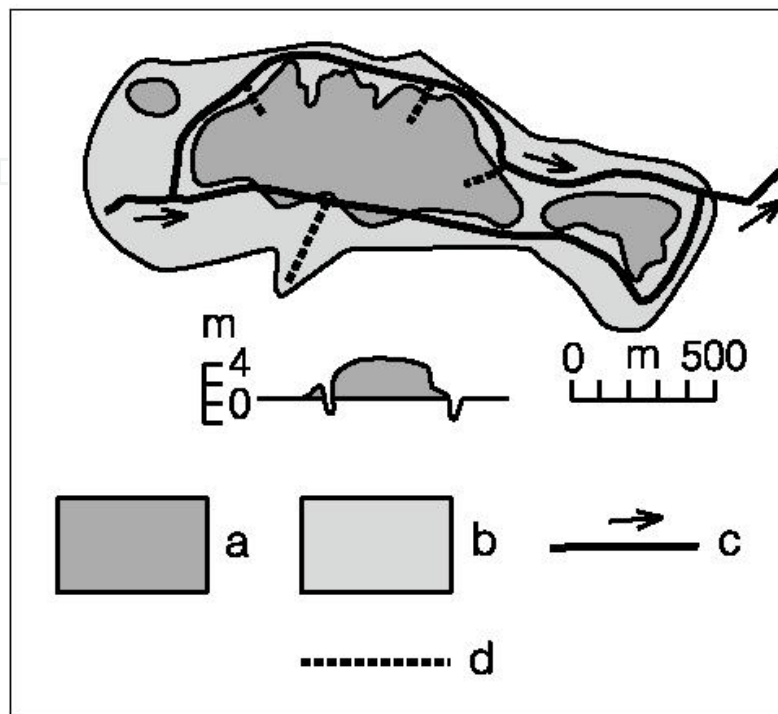
Scarp relief transitions from phase “a” to “e” or “f” most rapidly on southern and southwestern “warm” slopes of the peat dome. The slowest rate of change occurs on the opposite slopes. This suggests that peat is washed away during early spring snow melting periods, mainly.



**Figure 10.** Changes in relief of peat bog scarp since peat extraction is halted. a-f- phases in scarp relief changes, g- peat deposit, h- sub-peat material, i- younger post-peat area, j- bog slides, k- bogflows, l- peat hollows with water, m- shallowed hollows without water.

Edge streams, which used to flow around peat domes, became deeply incised ditches ringing the peat dome and linked with large regulated streams as well as short ditches draining younger post-peat areas and peat dome remnants (Fig. 11). The purpose of the drainage work was to dry the wet edge zone and younger post-peat areas as well as to accelerate water drainage away from the peat bog (Łajczak 2007). The following factors contributed to increasingly abrupt water discharge during flood events: 1) complete extraction of peat deposits across large older post-peat areas, with poorly permeable clayey parent material becoming exposed, 2) some extraction of peat deposits in younger post-peat areas and peat dome remnants, 3) straightening of stream channels, 4) increases in stream gradients. The result is the formation of gravel-bottom braided channels in the case of even small streams with a local tendency to aggradation. This is a sharp contrast to the earlier sinuous stream channels with a stable cross section (Łajczak 2007, 2011).

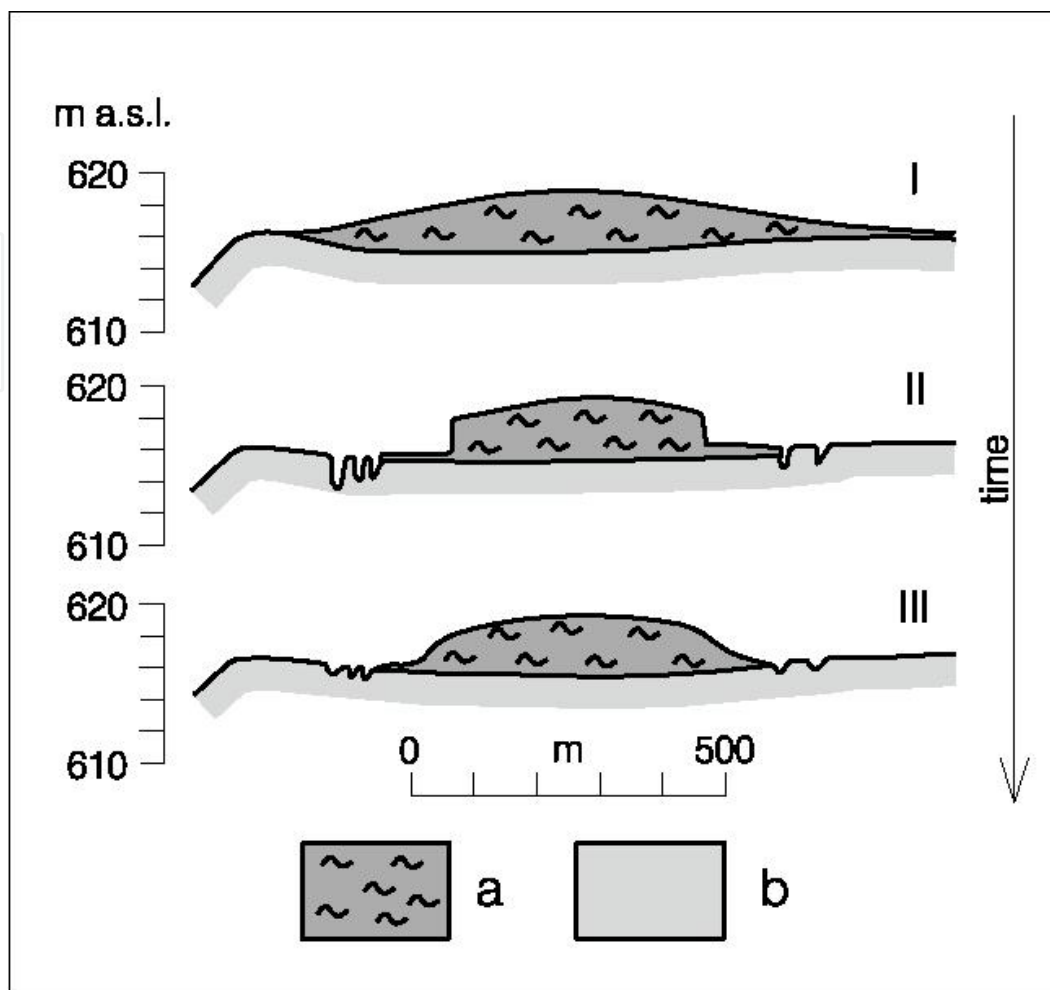




**Figure 11.** Example of ditches draining anthropogenically disturbed raised bog in the Orawsko-Nowotarska Basin: plan-view and profile. a- remnant of peat dome, b- younger post-peat area, c- girdling ditch, d- other ditch.

### 5.6. Peat bog revitalisation

Peat extraction has been declining in the Orawsko-Nowotarska Basin for more than two decades. This type of human impact has ceased to exist in the Bieszczady Mountains (Łajczak 2007, 2011). Drainage ditches are overgrown with vegetation due to a lack of maintenance and are effectively retarding the flow of water. This helps create wetlands in younger post-peat areas, which are now becoming a secondary edge zone. Peat moss takes about three years to colonize fresh peat pits filled with water. The increasing sinuosity of stream channels regulated in the past helps to make secondary edge zones more wet. Streams become more sinuous as water undercuts stream channel banks, which leads to more shallow stream channels. Beaver dams built near peat bogs in the Bieszczady Mountains provide another means of retaining water in post-peat areas. Small manmade dams in the region perform the same function (Łajczak 2011). The increasingly wet secondary edge zone and the increasingly flat post-extraction scarp help make peat dome remnants more wet, which prevents the drying of peat and facilitates the growth of peat moss. The cross section of a raised bog at this stage of development is different than that at previous stage of bog development (Fig. 12). Differences in elevation across post-peat areas initially become smaller during the last stage of raised bog development. As the peat dome grows, so do differences in elevation. However, this process may be disrupted once again if more peat is extracted and dried.

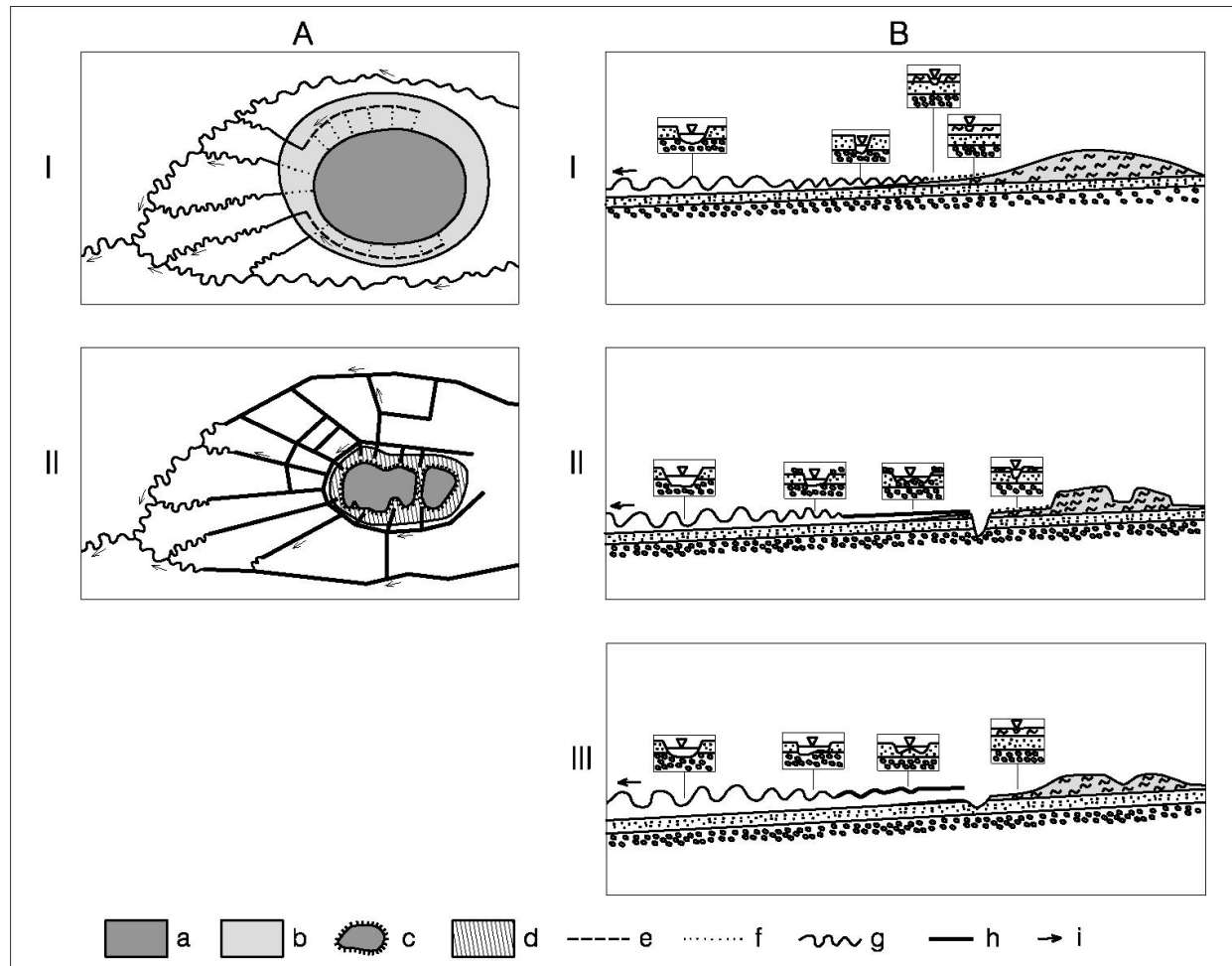


**Figure 12.** Cross-profiles through Bór na Czerwonym raised bog in the Orawsko-Nowotarska Basin in the periods: I- prior to human impact, II- at the end of peat extraction, and III- at the beginning of revitalisation process. a- peat deposit, b- sub-peat material.

## 6. Relief development patterns for raised bogs affected by human impact

Figure 13 shows changes in the extent and relief of a raised bog experiencing human impact. Period I shows a pre-human impact state. Period II shows an extraction and drying state. Period III shows the initial bog revitalisation state. Younger and older post-peat areas indicate areas of losses within the peat dome and the edge zone (period II). This was an area of stream channel regulation and drainage ditch construction. Extensive peat extraction primarily along the edges of the peat dome led to major changes in peat bog relief and major losses of water supplies (Łajczak 2007, 2009, 2011). Increases in the density of the drainage network surrounding peat dome remnants led to further drying of peat. An unintended consequence of stream channel regulation was streams becoming more shallow and wider. Another consequence was stream channels evolving into braided stream channels with a local tendency to aggradation. Today peat extraction has ended at most sites and drainage ditches are no longer being

maintained and are becoming more shallow. This helps make younger post-peat areas more wet, which helps them evolve into secondary edge zones. Another element of peat dome revitalisation is post-extraction scarps becoming more flat.



**Figure 13.** Typical changes in the extent and relief of a raised bog experiencing human impact. A- plan, B- profile. Periods: I- pre-human impact state, II- extraction and drying state, III- initial bog revitalisation state. a- peat dome, b- peat dome edge zone, c- remnant of peat dome surrounded by exploitation scarp, d- younger post-peat area, e- edge stream on outside of dome, f- short stream seeping out of peat dome and flowing across the muddy edge zone, g- meandering stream outside peat bog, h- ditch, i- direction flow. Schematic cross-sections of stream channels and ditches at various stages of their development are presented.

## 7. Discussion

The paper focuses on changes in raised bog relief in the Polish Carpathian Mountains. It documents bog characteristics that have not been documented before. The investigated peat bogs can be classified as valley-type based on their geomorphology (Ilnicki 2002), although each bog developed in a different mesoform. Raised bogs in the study area are not found exclusively on visible drainage divides, as other researchers seem to indicate (Tobolski 2000,

Ilnicki 2002), but tend to be found at lower elevations. Raised bogs with large peat domes may develop at any elevation in the study area. However, concave landforms are more likely to host peat bogs. This includes spring niches, old stream channels, the base of scarps of higher terraces, and the edges of alluvial fans. Numerous and stable groundwater outflows present within such landforms create the right conditions for low bogs to develop. As raised bogs evolve over time, these outflows maintain a high moisture level in the edge zone (Łajczak 2007, 2009).

Four stages of geomorphological development were identified for raised bogs in the study area. The last two stages are associated with human impact. Stage one is low bog development. Stage two is peat dome development. Peat domes grow depending on the relief of parent material and access to water. Gore (1983) as well as Obidowicz and Margielewski (2008) present a structural scheme of a large raised bog. The paper analyzes the geomorphological development of raised bogs found in a variety of mountain settings (e.g. valleys, basins) as well as analyzes peat bog development prior to human impact. These issues have been discussed only by a small number of researchers thus far (Kaule and Göttlich 1976, Rawes 1983, Obidowicz 1985, Carling 1986, Rhodes and Stevenson 1997, Bragg and Tallis 2001, Dykes and Warburton 2007, Łajczak 2007, 2011, Obidowicz and Margielewski 2008). New knowledge presented in this paper includes trends in bog development during the first and second stage of development relative to stable groundwater outflows facilitating bog formation. Assuming the view of Kaule and Göttlich (1976), raised bogs became ombrogenous-soligenous bogs at this stage, given that edge zones are still largely recharged by groundwater outflows.

The research literature tends to focus on historical and contemporary changes in peat bog relief caused by human impact (Bower 1961, Rawes 1983, Mallik et al. 1984, Evans 1989, Cooper and McCaan 1995, Rhodes and Stevenson 1997, Shaw et al. 1997, Bragg and Tallis 2001, Dykes and Warburton 2007, Łajczak 2007, 2011) in the form of sheep and cattle grazing, peat burning and peat drying. Peat erosion is of particular interest. However, a more in-depth analysis of contemporary changes in peat bog relief is difficult to find. This is especially true of papers published in the British Isles (Bower 1961, Evans 1989, Shaw et al. 1997, Bragg and Tallis 2001). In the study areas covered in this paper, peat extraction and drying are the main determinants of change in raised bog relief caused by human impact. Post-peat areas become larger and peat domes become smaller due to peat extraction by private landowners and industrial companies. Peat extraction, however, is on the decline. The paper also discusses changes related to the third stage of peat bog development by showing how just one form of human impact (e.g. peat extraction) can produce a variety of geomorphological effects based on how and when the impact had occurred.

The Polish research literature rarely covers ongoing changes in raised bog development – classified as stage four in this paper. The most important observations in this respect are the formation of a secondary edge zone in younger post-peat areas featuring shallow overgrown drainage ditches and peat pits as well as post-extraction scarps becoming more flat. Both processes assist in peat dome development (Łajczak 2007, 2011). On the other hand, the British research literature tends to focus on ongoing changes in peat bogs currently used for commercial purposes. In Great Britain and Ireland, both machine-based and manual harvesting of

peat produce landforms such as scarps and peat pits that maintain sharp contours for long periods of time (Cooper and McCann 1995, Latocha 2012). In addition, the end of sheep grazing does not lead to a rapid smoothing of landforms produced by trampling (Rawes 1983). While the rate of relief change in post-peat areas in the British Isles is rather slow, the corresponding rate for scarps and peat pits in raised bogs in the Polish Carpathians is rather fast. Latocha (2012) writes about post-extraction depressions in blanket bogs in Ireland, which are still ringed by vertical scarps, even though peat extraction had ended more than 50 years ago at a number of these sites. The scarps in Ireland are stabilized by rapid grass growth. However, older peat pits are much more shallow than younger peat pits, as their bottom is always wet. In the study area in the Polish Carpathians, scarps become overgrown mainly by bushy plants and pine and this takes more time. On the other hand, peat moss first encroaches upon peat pits and drainage ditches (Łajczak 2007, 2011). The burning of peat is a key factor behind the deterioration of upland and mountain blanket bogs in the British Isles (Rhodes and Stevenson 1997). However, this factor ceased to be a key factor in the Polish Carpathians in the early 20<sup>th</sup> century (Łajczak 2007, 2011).

## 8. Conclusions

The most important the author's findings are:

- the younger the fragments of Quaternary accumulation landforms in the studied areas, the more expansive the raised bogs used to be,
- almost of the bogs are classified as ombrogenous or ombrogenous-soligenous,
- the key change during the first two phases of peat bog relief development is fossilization of concave landforms, which become filled in by low bogs and then transitioned into raised bogs,
- another tendency in raised bog development is the shift towards lower elevation which now feature thicker peat deposits,
- among various manners of human impact on the peat bog relief for the last centuries, the peat extraction alters bog relief in the most visible of ways,
- the most visible and most rapidly changing elements of relief in bogs affected by human impact are extraction scarps,
- since the second half of the 20<sup>th</sup> century the younger post-peat areas are more wet, which helps them evolve into secondary edge zone of the bogs

One of the most urgent issues affecting Polish environmental conservation policy is the designation as reserves or as sites of ecological interest all the peat bogs studied that form a peatland complex unique at the European scale. A provision of legal protection for peat bogs will require some financial compensation for the local owners. Another way in which the local population should be able to improve their standards of living would be the development of



eco-tourism (walking, cycling, horse-riding) promoting the natural qualities of the sprawling mountain bogs.

Well preserved peat domes constitute a valuable component of the studied areas landscape unique at the Carpathian scale. In the past the post-peat areas were converted to pastures, meadows or arable land. Taking into account mountain topography, cool climate and especially low values of local clay soils for agriculture, the post-peat areas should be treated as wastelands or as meadows and pastures.

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