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Hydrological conditions of peatland formation based on a dynamic curve of a biogenic sediments sequence – a new proposal

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Abstract

The aim of the study was to propose a so called dynamic curve for identification of hydrological conditions of peatland formation. This method facilitates interpretation of accumulation processes based on sequence of biogenic sediments depending on variable hydrological conditions. Eleven types of hydrological conditions (HC) were distinguished and characterized with reference to ecohydrological interrelations governing the formation of peatlands. Each HC type was associated with specific peat type and species rendered in a classification for Central Europe. When employing a synthetic description of the identified HCs, it is possible to use the dynamic curve to provide a graphical representation of a hydration status for a geological profile and a general interpretation of the course of changes in water conditions during peatland development. The discussed method is somewhat simplified but it can be used for general interpretation of hydrological conditions of peatland development and would not require some highly specialized analyses. Such an approach may prove sufficient, particularly in engineering practice.

Key words: *biogenic sediments sequence, dynamic curve, peatland geology, peatland hydrology, plant macrofossils*

INTRODUCTION

Peatlands are specific ecosystems capable of accumulating residues of peat forming plants and thus formation of peat deposits. Functioning of these ecosystems depends primarily on such factors as hydrology, climate, chemistry, morphology and vegetation. These factors were used for developing numerous peatland classification systems and for explaining the patterns of their distribution [LINDSAY 2016; VITT 2006]. Most European classifications distinguish peatland types based on ecological and hydrological criteria. The ecological criterion defines the type of water supply, which determines trophic conditions of

a habitat and thus species composition of peat forming plants (e.g. KULCZYŃSKI [1939–1940; 1949]; OŚWIT [1975]; DAMMAN, FRENCH [1987]; TOBOLSKI [2000]; WHEELER, PROCTOR [2000]). Peats are formed when plant residues are accumulated in the conditions of permanent paludification. One of their most important roles is archiving the history of natural environment. This is possible thanks to certain preservative properties that allow for a survival of easily destructible artefacts, such as plant macrofossils (e.g. CHAMBERS, CHARMAN [2004]; TOBOLSKI [2004]). Plant residues composition indicates the type of peat and reflects hydrological conditions of the peat-forming process (e.g. OŚWIT [1977]; OKRUSZKO

[1983]; TUITILLA *et al.* [2007]). An analysis of plant residues may help in reconstructing subfossil communities and origin of a peatland. Peat types identified at various depths document plant communities prevailing at different times. Therefore, interpretation of a peat sequence may help in revealing the history of peatland formation.

Geology of peatlands is a rich source of data on both biotic and abiotic environments. First and foremost, it is widely used in paleoenvironmental studies to reconstruct hydrological changes and to understand hydrogeological determinants of peat-forming ecosystems (e.g. TOBOLSKI [2004]; ANDERSSON, SCHONING 2010)). The information retained in peat sediments allows for investigating climatic changes, dynamics of peat formation and carbon accumulation, and human impact on the peatland and its surroundings (e.g. BARBER [1993]; MAUQUOY *et al.* [2008]; LAMEN-TOWICZ *et al.* [2009]).

Modern high-resolution paleoenvironmental reconstructions use a multi-proxy approach based on quantitative abiotic and biotic proxies (e.g. VAN DER KNAAP *et al.* [2011]; GALKA *et al.* [2017]). Investigation of peatland paleohydrology involves not only plant macrofossils analysis but also pollen and non-pollen palynomorph analysis (e.g. testate amoebae), peat humification, and ash content that are supplemented by dating (e.g. ^{14}C method, dendrochronological method). Reconstruction of peatland paleo-water tables based on single-proxy analysis (e.g. plant macrofossils only) is less reliable than an interpretation involving multiple methods [VÄLIRANTA *et al.* 2012]. Although the multi-proxy approach provides a more comprehensive and reliable interpretation of peatland development conditions, some analyses require specialized background and scientific expertise.

The aim of the study was to present a proposal of using a so called dynamic curve for identification of hydrological conditions of peatland formation. This method may be used for general interpretation of the accumulation process based on the sequence of biogenic sediments depending on changes in source and state of water supply. It was developed with reference to a peat classification system commonly used in Poland. The study is intended at the presentation of the method alone, which is why detailed results of plant macrofossil analysis that serve as a basis for peat type identification are not presented here. At this stage, it should be treated as a preliminary proposal, as it requires validation against other methods of multi-proxy type used for paleoenvironmental reconstruction to determine its error.

MATERIAL AND METHODS

Peatland formation was investigated based on dynamic curves in 16 sites located in different regions of Poland (Fig. 1). Table 1 lists their coordinates and location within physico-geographical units (macro- and mesoregions) according to KONDRACKI [2011]

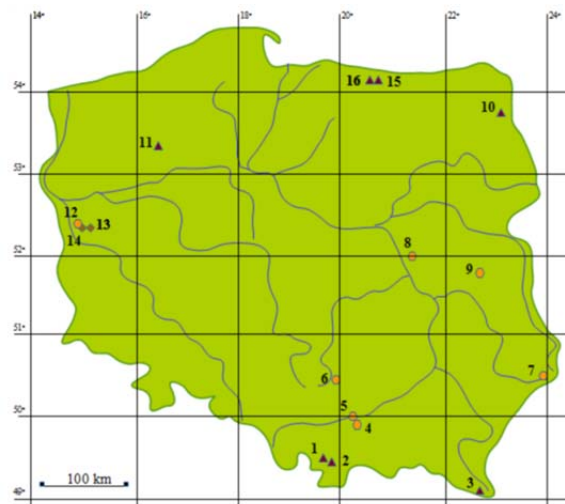


Fig. 1. Distribution of the investigated peatlands in Poland; type of peatland: ◆ fen, ● transitional bog, ▲ raised bog, 1–16 = numbers of peatlands – explanations in Tab. 2; source: own elaboration

and in a relief. Mean annual temperature and precipitation for the multi-year period of 1951–2000 were provided for the nearest weather station after WOŚ [2010] – Table 1.

Geological surveying of the peatlands was conducted along transects laid out in a way that reflected representative features of the sites. We present selected typical geological profiles for which the dynamic curves were developed. Drillings down to the mineral substrate were performed with an Instorf corer (Eijkelkamp) equipped with a 50 cm cylinder of 5 cm diameter. The sampled sediments were examined in a laboratory. A degree of peat decomposition [PN-G-04595; TOBOLSKI 2000] and composition of plant macrofossils were assessed with a microscopic method using available identification keys [KAC *et al.* 1977; MAUQUOY, VAN GEEL 2007; TOBOLSKI 2000]. To remove humus, the peat suspension was washed on a 0.2 mm mesh screen. Each sample was used to prepare three slides that were examined under a microscope at a magnification of 100–400 times. Ash content in the sediments was determined based on loss on ignition at 550°C in a sample previously dried to a constant weight, and carbonate content was assessed using Scheibler's method. The units of peat (types and species) were identified on the basis of plant macrofossils composition according to a genetic classification by TOLPA *et al.* [1967; 1971], and the types of gytja as per ILNICKI [2002].

Peatland zero boundary (min peat thickness 0.3 m) was identified using a metal probe, and then it was used for calculations of peatland area. Average thickness of peat and gytja was assessed as described in guidelines for peatland documentation [MR 1959]. Based on a source of water supply predominant type of hydrological feeding was determined for individual peatlands [DEMBEK, OŚWIT 1992; OKRUSZKO 1983].

Table 1. Basic physiographic and climatic characteristics of the investigated peatlands

No	Peatland name	Physicogeographic unit acc. to KONDRACKI [2011]		Geomorphological location	Mean annual for the period 1951–2000		Geo-graphical coordinates
		macroregion	mesoregion		P, mm	T, °C	
1	Puścizna Wielka	Orawa–Podhale depression	Orawa–Nowy Targ Basin	terrace within alluvial cone of the ice-marginal valley of the Czarny Dunajec River	1 111	6.1	49°26'54"N 19°46'10"E
2	Bór za Lasem	Orawa–Podhale depression	Orawa–Nowy Targ Basin	terrace within alluvial cone of the ice-marginal valley of the Czarny Dunajec River			49°25'30"N 19°48'18"E
3	Wolosate	Eastern Beskidy	Western Bieszczady	higher fluvial terrace of the Wołosatka stream	670	8.0	49°04'46"N 20°39'36"E
4	Targowisko	Sandomierz Basin	Bochnia Foothills (Wieliczka–Gdów Plateau)	old river-bed of the Raba River	666	7.9	49°59'20"N 20°18'04"E
5	Wielkie Błoto	Sandomierz Basin	Bochnia Foothills (southern and middle part) Nadwiślańska Lowland (northern part)	post-glacial depression on the older fluvial terrace of the Wisła River			50°1'7"N 20°16'30"E
6	Błonie	Nida Basin	Miechów Upland	valley of the Uniejówka River	628	7.3	50°27'21"N 19°54'08"E
7	Wojślawka	Lublin Upland	Grabowiec Height	valley of the Wojślawka River	574	7.4	50°56'23"N 23°26'26"E
8	Całowanie	Middle Mazowsze Lowland	Middle Wisła Valley	higher sandy dune terrace of the middle Wisła River valley	510	7.9	51°59'33"N 21°22'12"E
9	Wieprz – Krzna (near Radzyń Podlaski)	South Podlasie Lowland	Łuków Plain	valley of the Białka River	532	7.5	51°50'58"N 22°52'20"E
10	Koniuszki (upper Biebrza basin)	North Podlasie Lowland	Biebrza Basin	valley of the upper Biebrza River	587	6.2	53°41'45"N 23°29'38"E
11	Kłębowiec	South Pomeranian Lakeland	Wałcz Lakeland	valley of the Dobrzyca River	544	8.4	53°19'38"N 16°26'51"E
12	Bielice	Lubusz Lakeland	Torzym Plain	flow-through lake in the Ilanka River valley	588	8.4	52°21'20"N 14°59'07"E
13	Pniów I	Lubusz Lakeland	Torzym Plain	evorsion lake			52°20'56"N 15°01'16"E
14	Pniów II	Lubusz Lakeland	Torzym Plain	evorsion lake			52°20'58"N 15°00'49"E
15	Piersele	Staropruska Lowland	Sępapol Plain	kettle hole	623	7.1	54°21'02"N 20°40'10"E
16	Warszkajty	Staropruska Lowland	Sępapol Plain	kettle hole			54°21'07"N 20°38'27"E

Explanations: P = precipitation, T = air temperature. Source: own elaboration.

Table 2. Hydrological conditions for dynamic curves of biogenic sediment sequence in peat deposit

Symbol	Hydrological conditions (HC)
0	no peat-forming process
I	depressions in the terrain, lake basins filled with water; sedimentation processes of bottom deposits
II	nearly all year long flood, predominantly stagnant water with no distinct movements and supplemented with precipitation A.1.1 [*] ; 2, 3, 4, 5 ^{**}
III	ombrogenic-inundation water regime with decreasing inundation; higher location in a terrace system, less often floods in valleys, river accumulation phase A.1.2 [*] ; 6, 7, 8 ^{**}
IV	periodic groundwater inundation, short-term river floods followed by decrease in the peatland hydration A.1.3, A.2.3 [*] ; 12, 13, 14 ^{**}
V	flow through (drainage) water regime, constant supply of groundwater sometimes combined with inundation water; A.2.1, A.2.2 [*] ; 9, 10 ^{**}
VI	undecided hydrological regime; permanent but very weak water drainage or its complete cessation, ombrogenic-flow through water regime with weak share of the latter B.1, B.2 [*] ; 15, 16, 17 ^{**}
VII	ombrogenic water regime; progressive rise of water level in the peat with periodic (seasonal) fluctuations of its location; 20 ^{**}
VIII	ombrogenic water regime; accumulation of rainwater in peat maintained by capillary action, leading to rise in water level in peat; water level rises with progression of hollow-hummock cycle; hollows in hollow-hummock cycle or "treeless-hollow phase" 18 ^{**}
IX	ombrogenic water regime; lowering of water level, hummocks in hollow-hummock cycle or "hummock-forest phase" 19, 21, 22, 24 ^{**}
X	secondary decomposition of organic mass caused by frequent and considerable lowering of water level, amorphous peat XI ^{**}
D	inhibition of peat formation process due to peatland drainage; initiation of degradation (moorsh forming process)

* Symbols denoting hydrological conditions according to the classification of peatlands by KULCZYŃSKI and commented on by OKRUSZKO and OŚWIT [1991].

** Peat species numbers according to the classification of TOŁPA *et al.* [1976].

Source: own elaboration based on LIPKA [2000] and LIPKA, ZAJĄC [2014].

Table 3. Quantitative and qualitative data on the investigated peatlands

No	Peatland name	Area ha	Type of hydrological feeding	Peatland type	Peat deposit type	Thickness of peat/gyttja, m		Dominant peat species	D, % mean (range)	A, % mean (range)	References
						mean	max				
1	Puścizna Wielka	482	ombrogenous	R	R	2.79/-	6.25/-	<i>Eriophoro-Sphagneti</i>	16.5 (5.0–55.0)	2.6 (1.0–7.0)	LIPKA, ZAJĄC [2014]
2	Bór za Lasem	55	ombrogenous	R	R	1.80/-	3.65/-	<i>Eriophoro-Sphagneti</i>	30.0 (5.0–65.0)	2.2 (1.0–5.0)	LIPKA, ZAJĄC [2014]
3	Wolosate	4	soligeneous-ombrogenous	R	R	1.95/-	3.70/-	<i>Eriophoro-Sphagneti</i>	45.0 (35.0–50.0)	6.9 (3.05–18.30)	LIPKA, GODZIEMBA-CZYŻ [1970], LIPKA [1995]
4	Targowisko	25	soligeneous-fluvio-geneous	F	F	3.53/1.09	4.50/1.80	<i>Cariceto-Phragmiteti</i>	35.0 (30.0–65.0)	26.5 (13.4–41.3)	un. sup.
5	Wielkie Błoto	265	soligeneous-fluvio-geneous	F	F	1.72/0.75	4.30/2.10	<i>Cariceto-Phragmiteti</i>	35.0 (25.0–65.0)	23.1 (11.5–38.2)	LIPKA [1973; 1989], LIPKA <i>et al.</i> [2006] sup.
6	Błonie	100	soligeneous-fluvio-geneous	F	F	2.34/-	5.00/-	<i>Cariceto-Phragmiteti</i>	45.0 (15.0–85.0)	26.0 (15.2–35.2)	LIPKA <i>et al.</i> [1977], LIPKA [2000] sup.
7	Wojśławka	157	soligeneous-fluvio-geneous	F	F	2.44*	5.20*	<i>Cariceto-Bryaleti</i>	30.0 (25.0–65.0)	11.1 (7.8–17.2)	LIPKA [2000] sup.
8	Całowanie	1200	soligeneous-fluvio-geneous	F	F	2.34/0.60	3.50/1.00	<i>Cariceto-Bryaleti, Cariceto-Phragmiteti</i>	45.0 (25.0–65.0)	20.1 (6.7–49.15)	OŚWIT, DEMBEK [2001] sup.
9	Wieprz-Krzna (near Radzyń Podlaski)	1710	fluviogeneous	F	F	1.5/0.76	3.75/1.7	<i>Cariceto-Phragmiteti</i>	40.0 (30.0–65.0)	10.2 (7.1–16.5)	LIPKA [1984; 2000] sup.
10	Koniuszki (Basen Górnej Biebrzy)	70	soligeneous-fluvio-geneous	F	F	3.49/0.90	6.75/1.50	<i>Cariceti, Cariceto-Bryaleti</i>	35.0 (25.0–75.0)	12.7 (7.2–22.4)	LIPKA [2000]
11	Kłębowiec	54	soligeneous-fluvio-geneous	F	F	1.03/0.98	1.75/1.25	<i>Alneti</i>	40 (35.0–60.0)	16.6 (1.9–26.4)	un. sup.
12	Bielice	65	soligeneous-fluvio-geneous	F	F	2.86/1.95	5.75/5.25	<i>Alneti</i>	49.0 (35–60)	22.6 (8.5–31.4)	LIPKA, FRANKIEWICZ [1981] sup.
13	Pniów I	1.5	ombrogenous	T	R	1.93/-	2.10/-	<i>Eusphagneti</i>	15.0 (10.0–25.0)	10.4 (4.8–21.2)	un. sup.
14	Pniów II	0.5	ombrogenous	T	R	7.77/0.65	8.25/0.75	<i>Eriophoro-Sphagneti</i>	25.0 (10.0–55.0)	7.1 (4.4–14.9)	un. sup.
15	Piersele	28	topogeneous-ombrogenous	R	R	2.46/1.05	5.10/2.10	<i>Eriophoro-Sphagneti</i>	33.0 (30.0–60.0)	6.2 (2.2–14.1)	un. sup.
16	Warszkajty	8	ombrogenous	R	R	4.95/0.54	10.0/0.75	<i>Eusphagneti</i>	7.0 (5.0–10.0)	4.8 (2.6–9.2)	un. sup.

Explanations: type of peatland/peat deposit: F = fen, T = transition, R = raised, D = degree of peat decomposition, A = ash content, un. = unpublished data; sup. = supplemented data; * = whole deposit. Source: own elaboration.

Characteristic qualitative and quantitative data on peatlands are presented in Table 3. Some studies were conducted in the years 1968–1980 when an inventory and documentation of peatlands in Poland were performed. These findings were supplemented in later years and partially published (references provided in Table 3).

DYNAMIC CURVE OF THE BIOGENIC SEDIMENT SEQUENCE

From a geological perspective, peat is a quaternary biogenic deposit classified as a sedimentary rock [MIZERSKI, SYLWESTRZAK 2002], so it may be de-

scribed using lithological criteria and subjected to petrographic characteristics [TOBOLSKI 2004]. The characteristics of the sedimentary rock stratigraphy involve determination of sedimentary environments in which the rocks were formed. Their origin and history may be described using a dynamic curve of a lithostratigraphic profile that is a petrographic approach [ALEXANDROWICZ 1978] reflecting the dynamics of sedimentary environments.

Here we propose to use a similar dynamic curve for peatlands, as from a petrographic perspective peat is a biogenic deposit formed in a sedimentary environment conditioned by water presence. Analysis of hydrological and phytosociological relationships re-

sulted in distinguishing eleven types of hydrological conditions (HC) (Tab. 2) that may facilitate peat formation (in earlier papers e.g. LIPKA [2000], LIPKA, ZAJĄC [2014] “hydrological conditions” were called “aquatic environments”). They are associated with specific peat species set out in the classification for Central Europe published by TOLPA *et al.* [1967; 1971]. This classification is based on a genetic association of peat with botanical composition of the plant communities of which it was formed.

Designated HC (Tab. 2) were marked with symbols (0, I, II ... D) and described with reference to the type of biogenic sediment (bottom deposits, peats) considering source and movements of supplying water and state of a peat-forming process (peat accumulation or degradation). Peat species that were formed by specific phytocoenoses may be treated as “indicators” of typical HC (water quality and its table within a peatland) prevailing in a given period. When employing a synthetic description of the identified HCs, it is possible to use the dynamic curve to provide a graphical representation of a hydration status for a geological profile and a general interpretation of the course of changes in water conditions during peatland development. In graphical presentation dynamic curve is a „stepped” line, which is a result of a time scale, frequency of sample collection. In fact, dynamics of water conditions followed by changes in peat-forming vegetation is reflected by smooth curvilinear course.

The proposed dynamic curve method is a simplified tool that yields data on the dynamics of changes in the ecohydrological system of a peatland but without explaining their causes.

RESULTS AND DISCUSSION

GENERAL CHARACTERISTICS OF THE EXAMINED PEATLANDS

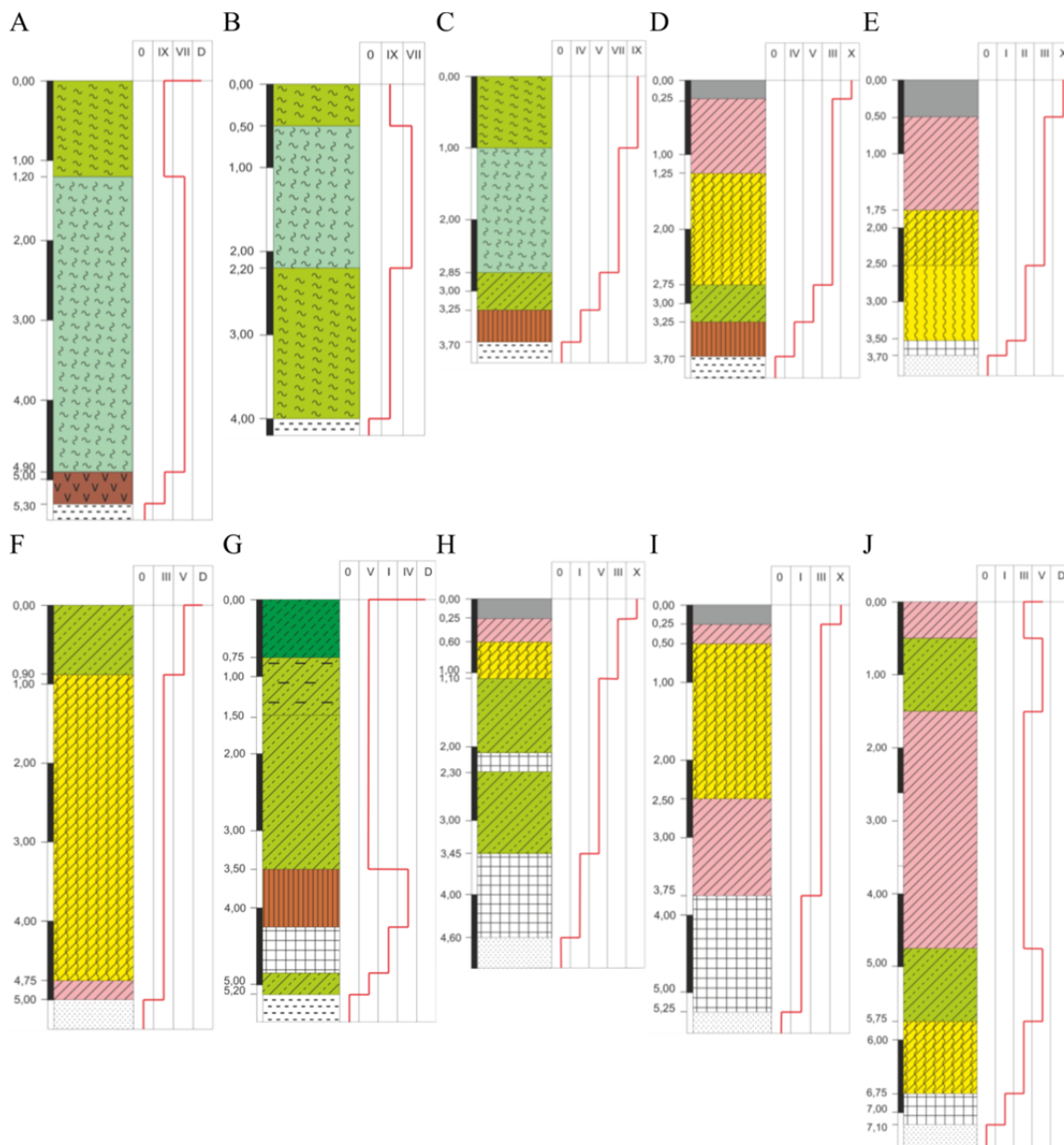
The examined peatlands were of fen (9), bog (5) and transitional (2) type. Bogs were characterized by ombrogenic water supply, and soligenic-fluviogenic feeding prevailed in fens (Tab. 3). Gytija of variable thickness underlaid peats in nine sites. The greatest mean (1.95 m) and maximum (5.25 m) thickness of this sediment was noted in Bielice (No 12) peatland. A dominant fen peat species was sedge-reed (*Cariceto-Phragmiteti*), while alder (*Alneti*) and reed (*Phragmiteti*) peats were less common. Bog peats were represented mainly cotton grass-*Sphagnum* (*Eriophoro-Sphagneti*) and hummock *Sphagnum* (*Eusphagneti*). These peats often formed several meters thick layers. In general, bog peats showed lower decomposition degree as well as ash content than fen peats. Transitional peats were rare and formed only shallow layers in the roof and bottom of the deposits. Considering total thickness of peat and gytija, the thickest deposits were identified in Warszkajty (10.75 m), Bielice (10.0 m) and Pniów II (9.0 m) – Table 3.

PEATLAND DEVELOPMENT BASED ON A DYNAMIC CURVE

Abundant data on wetlands, defined as areas covered with materials accumulated at the surface as a result of water presence or with vegetation adapted for life in saturated soil conditions (so peatland and non-peatland areas), allowed for identification of considerable typological differences among geomorphological zones and physico-geographic regions of Poland [DEMBEK *et al.* 2000; ILNICKI 1996; OKRUSZKO *et al.* 2001; ŻUREK 1987]. A relationship was also confirmed between a landscape position of wetland and major source of water (precipitation, groundwater or surface waters), as the supply and runoff conditions determine the level and fluctuations of water table and therefore shape the ecohydrological conditions [DEMBEK, OŚWIT 1992; ŁAJCZAK 2013; OKRUSZKO 1992]. To illustrate these differences, the dynamic curves were developed for selected sites from different regions of Poland, that were formed under diverse geomorphological conditions. They were divided into three categories: mountain peatlands (Fig. 2A–C), peatlands formed in old glacial area of southern, eastern and central Poland (Fig. 2D–J), and peatlands developed in young glacial area of northern Poland (Fig. 2K–P).

In mountainous regions, the peatlands were formed within watersheds and flattened or basin-shaped areas of slopes, particularly those covered with poorly permeable mineral substrate. Climatic conditions prevailing in these regions favoured peatland development. An increase in precipitation and a decrease in air temperature along with height promote development of raised bogs. Young glacial area has highly diversified landforms (outwash plains, moraine uplands, tunnel valleys, ice marginal valleys, etc.) with plentiful depressions. In this relief, peatlands often develop within lakes or depressions of different size. Contrary to this, old glacial area is characterized by a low number of depressions and greater denudation. In general, peat covered areas in this relief occurred rather within ice-marginal valleys and plains than highlands. Peatland development took place in various locations of extensive river valleys and was determined by a supply of surface and groundwater (see ŻUREK [1987]; DEMBEK *et al.* [2000]).

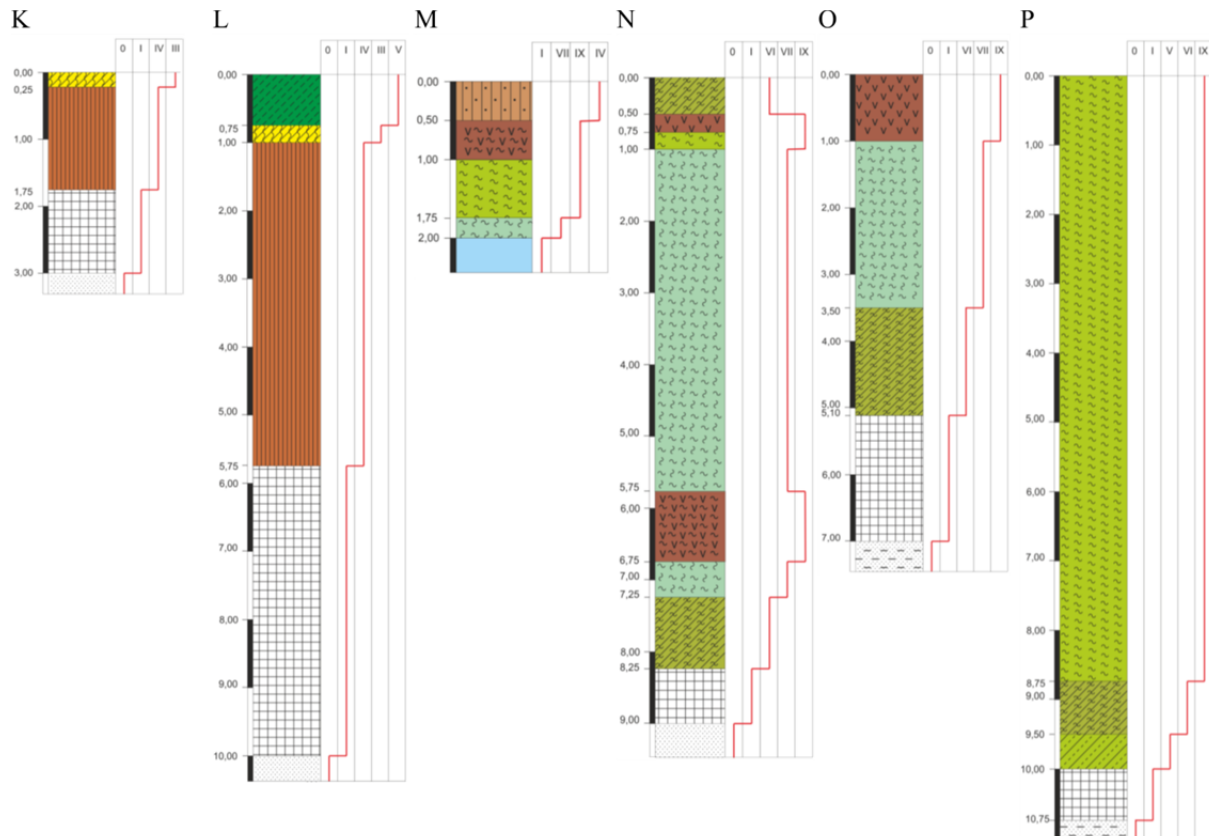
Below are examples of using dynamic curves for investigating hydrological determinants of peatland development based on the sediment sequence. The symbols of hydrological conditions (HC) in Figure 2 and in the text discussing the figures are as defined in Table 2. However, it should be stressed that complete recognition of peatland origin requires an analysis of a number of geological profiles from representative zones of the investigated sites, as they provide data not only on sediment sequence in vertical layout but also on their zonal variability in horizontal arrangement.



MOUNTAIN PEATLANDS

Puścizna Wielka (No 1) (Fig. 2A) and Bór za Lasem (No 2) (Fig. 2B) bogs located in Orava–Nowy Targ Basin were formed as a result of paludification of a poorly permeable clay substrate. Uplifting of the bog domes was associated with growing prevalence of ombrotrophic water supply that resulted in extreme oligotrophization of habitat. Peat was usually formed in HC VII, that is when progressive rise of water level in the peat was associated with its periodic fluctuations. These hydrological conditions were conducive to the formation of cotton grass-*Sphagnum* peat of considerable thickness. When lowered water level was maintained for longer periods, corresponding to HC IX, hummock *Sphagnum* peat was formed or, as in bottom layers of Puścizna Wielka bog, pine wood (*Pineti*) peat.

A Wołosate bog (No 3) (Fig. 2C), located in Western Bieszczady, has a different origin. Its formation began with accumulation of fen peats in the valley of the Wołosatka. At the bottom of the deposit alder peat was formed in HC IV, i.e. under short-time river inundation. The overlying sedge-moss (*Cariceto-Bryaleti*) peat indicated a gradual increase in feeding of the peatland with groundwater (HC V). Geological profile of this peatland revealed the presence of fen peats directly followed by bog peats of cotton grass-*Sphagnum* (HC VII) and hummock *Sphagnum* (HC IX) type. Their presence was due to the cessation of water drainage through the peatland and a shift towards ombrogenic alimentation. A thin layer of transitional peat, covering a layer of the fen peat, was found only in the central part of the peatland [LIPKA 1995]. According to KULCZYŃSKI [1939–1940; 1949], radical hydrological changes leading to oligotrophiza-



Explanations:

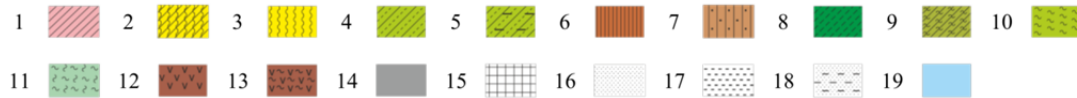


Fig. 2. Dynamic curve of the lithological sequence in peat deposit: A: Puścizna Wielka (No 1) (source: LIPKA, ZAJĄC [2014], changed); B: Bór za Lasem (No 2) (source: LIPKA, ZAJĄC [2014], changed); C: Wołosate (No 3); D: Targowisko (No 4); E: Wielkie Błoto (No 5); F: Błonie (No 6) (source: LIPKA [2000], changed); G: Wojślawka (No 7) (source: LIPKA [2000], changed); H: Całowanie (No 8); I: Wieprz-Krzna near Radzyń Podlaski (No 9) (source: LIPKA [2000], changed); J: Koniuszki (Basen Górnej Biebrzy) (No 10) (source: LIPKA [2000], changed); K: Kłębowiec (No 11); L: Bielice (No 12); M: Pniów I (No 13); N: Pniów II (No 14); O: Piersele (No 15); P: Warszkajty (No 16); 1 = *Cariceti* peat, 2 = *Cariceto-Phragmiteti* peat, 3 = *Phragmiteti* peat, 4 = *Cariceto-Bryaleti* peat, 5 = *Cariceto-Bryaleti* peat with clay admixture, 6 = *Alneti* peat, 7 = *Betuleti* peat, 8 = *Bryaleti* peat, 9 = *Sphagno-Cariceti* peat, 10 = *Eusphagneti* peat, 11 = *Eriophoro-Sphagneti* peat, 12 = *Pineti* peat, 13 = *Pino-Sphagneti* peat, 14 = humified peat, 15 = gyttja, 16 = sand, 17 = clay, 18 = clay with admixture of sand, 19 = water; source: own elaboration

tion of habitats and gradual transformation of fens into bogs are very often related to geomorphological processes. In the case of Wołosate, these processes resulted in a transition of the peatland from the valley axis to a floodplain terrace due to deep erosion of the watercourse.

PEATLANDS OF OLD GLACIAL AREA

Wielkie Błoto (No 5) peatland (Fig. 2E) was formed in a post glacial depression within an older terrace of the Vistula ice marginal valley. Waterlogging and hindered water runoff (HC I) resulted in calcareous gyttja formation on the bottom of the depression. The layer of reed peat was formed in HC II, i.e. almost year-round inundation with predominantly stagnant water supplied mainly with precipitation water. As the intensity and importance of inundation in ombrogenic-inundation water regime of the peatland

decreased, reed vegetation gradually declined and sedge communities developed. This was reflected in peat sequence of sedge-reed, and then sedge (*Cariceti*) peats formed in HC III. The roof layer was an amorphous peat formed after drainage of a large part of the peatland in 19th century [LIPKA 1989], which resulted in a general decrease of groundwater level (HC X) and consequently degradation of substantial area of the peatland.

Formation of a fen Wojślawka (No 7) (Fig. 2G) was shaped mainly by the HC V. The peatland was formed in a closed depression layered with poorly permeable clay. Initial plant communities on the clay substrate formed a thin layer of sedge-moss peat covered with a shallow layer of gyttja (HC I). At the next stage, alimentation was based on constant supply of groundwater but inundation water was also periodically more or less important. Gyttja, in the conditions of short-term river flood (HC IV), was covered with

alder peat. Reduced intensity and duration of floods accompanied by an increase in ground water supply (HC V) favoured formation of sedge-moss peat. Periodic floods were evidenced by the presence of clay in the upper layer of this peat. When the inundation ceased, moss peat (*Bryaleti*) was formed in the roof layer of the deposit. Drainage of the peatland inhibited peat formation process and initiated its degradation (HC D).

PEATLANDS OF YOUNG GLACIAL AREA

A very deep Bielice (No 12) peatland (Fig. 2L) originated from a terrestrialization of postglacial flow-through lake in the valley of the Ilanka River. A considerably thick (4.5 m) layer of organic and calcareous gyttja (HC I) was formed at the bottom of the lake. When the depression shallowed, peatland formed under prevailing HC IV. Periodic inundation resulted in a formation of a nearly 5 m thick deposit of alder peat. Peat types in the roof layer indicated decreasing frequency and intensity of river flooding and increasing share of groundwater supply in the peatland hydrology. The roof zone included a thin layer of sedge-reed peat formed in HC III covered with moss peat formed in HC V characterized by drainage of groundwater, but with no flooding. A similar pattern of ecohydrological development was observed for a much shallower Kłębowiec (No 11) peatland (Fig. 2K).

Interesting sites of young glacial area are kettle hole mires that have been so far poorly recognized but have been recently attracting increasing attention of researchers (e.g. TOBOLSKI [2003]; LAMENTOWICZ *et al.* [2007]; KOWALEWSKI, ŻUREK [2011]). Examples include the peatlands around Pniów (No 13 and 14) (Fig. 2M, N) or Warszkajty (No 16) peatland (Fig. 2P). These are peatlands formed mainly in HC IX supplied with precipitation water. The peatlands Pniów II (No 14) (Fig. 2N) and Warszkajty were formed over gyttja sublayer (HC I). In the beginning, their development depended on the supply of groundwater. Accumulation of peat caused gradual isolation of the peatland area from the surrounding regional groundwater table and a transition to ombrogenic water supply. The profile of Warszkajty peatland revealed organic and calcareous gyttja covered with a thin layer of sedge-moss fen peat (HC V), over which *Sphagnum*-sedge (*Sphagno-Cariceti*) transitional peat was formed. The appearance of transitional peat indicated ombrogenic-drainage type of water regime, with a distinctly declining share of the latter (HC VI). No fen peat was detected over clay gyttja in Pniów II peatland. In both peatlands the transitional peat was covered by different types of ombrogenic peats depending on the hydration state of the peatland, sometimes of considerable thickness. Progressive rise of water level in peat with its periodic oscillations (HC VII) facilitated formation of cotton grass-*Sphagnum* peat (Pniów II). Lowered groundwater

level and so drier conditions, i.e. in HC IX, was conducive to the formation of thin layers of pine-*Sphagnum* (*Pino-Sphagneti*) or pine wood peats (Pniów I and II), indicating the “hummock-forest phase” of the peatland development, or hummock *Sphagnum* peat (in Warszkajty peatland it is a homogeneous, over 8 m thick layer). Warszkajty is a bog, while Pniów I and II are of transitional type. Pniów peatlands were formed in the HC VI and contain thin layers of transitional peats of birch (*Betuleti*) (Fig. 2M) or *Sphagnum*-sedge type (Fig. 2N), which indicated the presence of groundwater or nutritious runoff from surrounding areas. The peatland Pniów I (Fig. 2M) is a typical example of overgrowing of a kettle hole by a floating mat. A small, only 0.5 ha Pniów II (Fig. 2N) peatland originated in a similar way, and its original lake was completely terrestrialised.

The course of the presented dynamic curves indicated that the trajectory of vegetation changes and consequently peat sequence in a deposit were determined by changes in a hydrological factor, i.e. mainly quantity and quality of supplying water. This depends primarily on climatic and hydrogeological conditions, hydrographic network, fluctuations of ground water level, cessation or occurrence of long term floods or intensity of surface and groundwater supply (e.g. OŚWIT [1975]). Recent research demonstrated that the changes in hydrogeological conditions during development of peatlands were complex processes and might be due to different, sometimes overlapping causes. Peatland transformation may be caused by autogenic processes, e.g. plant succession resulting in terrestrialization and transition from a lake to a fen and finally a bog (e.g. KULCZYŃSKI [1939–1940; 1949]; HUGHES, BARBER [2003]; URBAN, TOKARZ [2014]). However, the expected direction of an autogenic succession might be modified by an external allogenic factor [TUUTTILA *et al.* 2007], such as climatic changes that particularly affect ombrotrophic bogs (e.g. GUNARSSON *et al.* [2003]; CHARMAN *et al.* [2006]; EDVARDSSON *et al.* [2012]), or anthropogenic pressure in the form of deforestation, drainage or fires (e.g. SILLASOO *et al.* [2011]; STIVRINS *et al.* [2017]). While interpreting the sequence of sediments in a deposit one should remember that hydrological changes may be of gradual but also of sudden and fierce nature, which may result in a lack of some transition stages in the series of succession (hiatus) (e.g. MAREK [1965]; OŚWIT [1975]). In this case, the arrangement of individual peats in the profile usually differs from the most common sequences. The sequence indicating anomalies in natural stages of a peatland development, e.g. the presence of sedge or reed peats over moss peats, fen peats over transitional ones or gyttja over fen peats usually reflected climate changes including increased humidity or rising sea level or local groundwater level, or was due to the anthropogenic pressure [ŻUREK 1993]. However, relative effects of internal (autogenic) and external (allogenic) processes on changes in hydrological conditions in a peatland,

and therefore in the peatland ecohydrology may be difficult to determine unambiguously, and the effects of a climate on changes in water table depth are in some cases overestimated [MORRIS *et al.* 2011; SWINDLES *et al.* 2012].

CONCLUSIONS

Considering the complexity of peatland paleoecology and paleohydrology, we presented a proposal of the dynamic curve method. The method and a concise description of hydrological conditions (HC) facilitating formation of particular biogenic sediments (bottom deposits, peats) constitute a simplified approach but the method can be used for general interpretation of local hydrological conditions of peatland formation that would allow for skipping some highly specialized research. This approach may prove useful particularly in engineering practice. It could be also helpful for specialists from other fields, e.g. geologists, biologists or representatives of administration or non-governmental organizations, who are not deeply involved in peat research. However, to refine the method and determine its error, it needs to be verified by the use of other methods (multi-proxy studies).

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Krzysztof LIPKA, Ewelina ZAJĄC

Warunki hydrologiczne powstawania torfowisk na podstawie krzywej dynamicznej sekwencji osadów biogenicznych – nowa propozycja

STRESZCZENIE

Celem pracy było przedstawienie propozycji wykorzystania tzw. krzywej dynamicznej do określenia warunków hydrologicznych powstawania torfowisk. Posługując się proponowaną metodą, można w prosty sposób zinterpretować przebieg procesu akumulacji na podstawie sekwencji osadów biogenicznych w zależności od zmieniających się warunków hydrologicznych. Mając na uwadze ekohydrologiczne zależności skutkujące powstawaniem torfowisk, wyróżniono i opisano jedenaście typów warunków hydrologicznych (HC), którym przyporządkowano określone gatunki torfu ujęte w klasyfikacji opracowanej dla obszaru środkowej Europy. Posługując się syntetycznym opisem wydzielonych HC, można, za pomocą krzywej dynamicznej, graficznie zilustrować stan uwodnienia profilu geologicznego oraz zinterpretować przebieg zmian stosunków wodnych w trakcie formowania się torfowiska. Zaproponowana metoda stanowi pewne uproszczenie, niemniej może być stosowana do ogólnej interpretacji warunków hydrologicznych powstawania złóż torfowych z pominięciem niektórych, wysoce specjalistycznych badań. Takie podejście może okazać się wystarczające zwłaszcza w praktyce inżynierskiej.

Słowa kluczowe: geologia torfowisk, hydrologia torfowisk, krzywa dynamiczna, sekwencja osadów biogenicznych, szczątki roślinne