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Morphological characteristics and lithological conditions of the spring-heads in the Knyszyńska Primeval Forest

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Abstract

The aim of the study was to determine the morphological characteristics of selected spring-heads in the Knyszyńska Primeval Forest and to identify lithological conditions in areas where groundwater flows to the surface. During the study, detailed bed level measurements of the spring-head areas were conducted. Lidar laser data obtained from the Central Department of Geodetic and Cartographic Documentation in Warsaw were also used for the analysis of morphometry. Based on the data, the detailed contour maps were created in the Surfer 12 programme and the basic parameters of the morphometry of the studied springs were determined. To detect lithological conditions, granulometric analyses were conducted and the filtration coefficient of aquifers in the individual spring-heads was calculated using Hazen and USBSC empirical models. Due to the morphological situation, the examined objects were classified as sub-slope and riverbank spring-heads. In terms of shape, spring-head alcoves are classified as basin-shaped, bowl-shaped and spindle-shaped alcoves. Different morphological processes prevail in each of these types. Basin-shaped alcoves are formed mainly by lateral erosion, bowl-shaped alcoves by seepage erosion, landsliding and accumulation in the bottom, spindle-shaped alcoves by seepage erosion, headward erosion, breaking and collapsing. In the investigated outflows of groundwater aquifers are sands and glacifluvial sands with gravel of varying grain size. The lithological variation of aquifers in the spring-heads, directly affects the rate of groundwater filtration in different parts of the alcoves, which in turn leads to different morphogenetic processes and results in changes in the morphology of the spring-head alcoves.

Key words: *aquifer, Knyszyńska Primeval Forest, spring-head, spring-head alcoves morphology*

INTRODUCTION

Springs, that is, natural, concentrated groundwater outflows are a specific element of the landscape. This is due to the fact that the area of the groundwater outflow is a place where the elements of the abiotic and biotic environment, the lithosphere, the hydrosphere and the biosphere are in contact [MONIEWSKI 2004]. For this reason, the interaction of the spring with the surrounding area is much farther than the place of the exfiltration of groundwater. Areas where the springs occur are places of various geomorphological processes such as seepage erosion, abrasion, linear erosion, slope processes, tunnel erosion, leaching, windthrow erosion [MAZUREK 2006; 2010; 2017; WROŃSKA 2006a]. At the same time, the intensification of processes typical for a given morphogenetic zone in areas of occurrence of springs is also generally higher than in the surrounding areas. Nevertheless, the role of groundwater outflows in forming surface in temperate climates is not fully appreciated [MAZUREK 2010; 2017].

The direct result of seepage erosion is creating spring alcoves or spring-head alcoves. It is a cavity on a slope or at its footstep, resembling a funnel or a small amphitheatre of varying depth and surface, usually not exceeding several hundred meters. In the systemic approach, the spring alcoves are treated as a part of the zero-order stream

[Schumm 1977], and in mountainous areas they are even identified and treated as part of the headwater [Wrońska-Wałach *et al*. 2013]. As landforms, spring-head alcoves differ from the landscape with different topographic, hydrological, biological and even topoclimatic characteristics. This specificity is already evident in the morphology and morphometry of the spring-head alcoves and is the most evident by surrounding them on three sides with higher terrain, the greater inclination of slopes and their exposure. Thus alcoves, considered only in morphological terms, are extremely interesting objects. Sediment studies in spring-head alcoves are relatively rarely conducted, except for biogenic and chemogenic sediments [Mazurek 2010; Mazurek, Paluszkiewicz 2013].

In the postglacial terrains of northwestern Poland, in the upper Parsęta River catchment area, Mazurek [2006; 2010] distinguished, on the basis of analysis of morphometric parameters, the types of basin-shaped, bowl-shaped and spindle-shaped alcoves. The author described in detail the environmental conditions of the formation of each type. Based on the analysis of morphogenetic processes in the spring-heads and bottom deposits, the variability of the roles of seepage erosion and slope processes in the development of the spring-head alcoves has been demonstrated. Mazurek [2010; 2017] has identified seepage erosion as one of the most important processes in the development of riverbeds and valley network under various environmental conditions. The geomorphologic studies of spring-heads located in early-glacial relief areas are scarce. Alcoves of varied sizes, sometimes referring to the axis of denudation valleys, were recognised on the Łódź Hills [Moniewski 1997; 2004]. The forest spring-heads in the Łódź region have been described in relation to their protection [Kurowski *et al*. 2008].

The first stocktaking of the Knyszyńska Primeval Forest spring-heads was carried out by Łoszewski [1984]. He drew attention to the richness of this type of objects in the forest areas and examined their discharge volume. The research confirmed the presence of over 400 groundwater outflows in the Knyszyńska Primeval Forest. Most studies on spring-heads have appeared while discussing hydrochemical and hydrobiological [Górniak, Jekatierynczuk-Rudczyk 1995; 1999; Jekatierynczuk-Rudczyk 2002; 2003; 2010] as well as environmental issues [Łoszewski 2000]. The physicochemical properties of water in relation to hydrogeological conditions of selected spring-heads from Krzemianka, Budzisk and Jałówka reserves were presented by Chomutowska and Kryjan [2014]. However, there is no analysis of the spring-head alcoves morphology in the late-glacial areas in the context of lithological deposits, geomorphology and geological structure.

The reasons mentioned above encourage to undertake geomorphological and sedimentological research of spring-head areas of the Knyszyńska Primeval Forest. The aim of the study was to determine the morphological, morphometric and geological-lithological conditions of selected spring-heads in the Knyszyńska Primeval Forest.

MATERIALS AND METHODS

METHODS

Field studies were conducted in April–July 2017. During the preliminary work the available materials were analysed and 10 spring-heads were selected in the Knyszyńska Primeval Forest: Budzisk, Budzisk-Migówka, Jałówka, Krzemianka, Łaźnie, Pieszczaniki A, Pieszczaniki B, Pólko, Pstrągownia and Radulin (Fig. 1). The morphological and morphometric features of all objects were determined. The width and total length of the spring-head alcoves were measured, the length and width of the bottoms of the alcoves, the perimeters and the surfaces of the bottoms, the height of the slope closing the alcove, the length of the outflow. The boundary between the slope of the alcove and the slope of the terrain in which the alcove was formed was usually clear and manifested by a greater inclination. More thorough field research was performed on 6 objects. Geomorphological charting of the surrounding areas was carried out.

Tachymetric measurements of altitude were made in Krzemianka, Łaźnie and Pstrągownia objects by the leveling string method. At the points of groundwater outflow and at the bottom of the alcove, sampling and lithographic charting were carried out in the Krzemianka, Łaźnie, Pieszczaniki A, Pieszczaniki B, Pólko and Pstrągownia objects. During the laboratory tests granulometric analyses were performed.

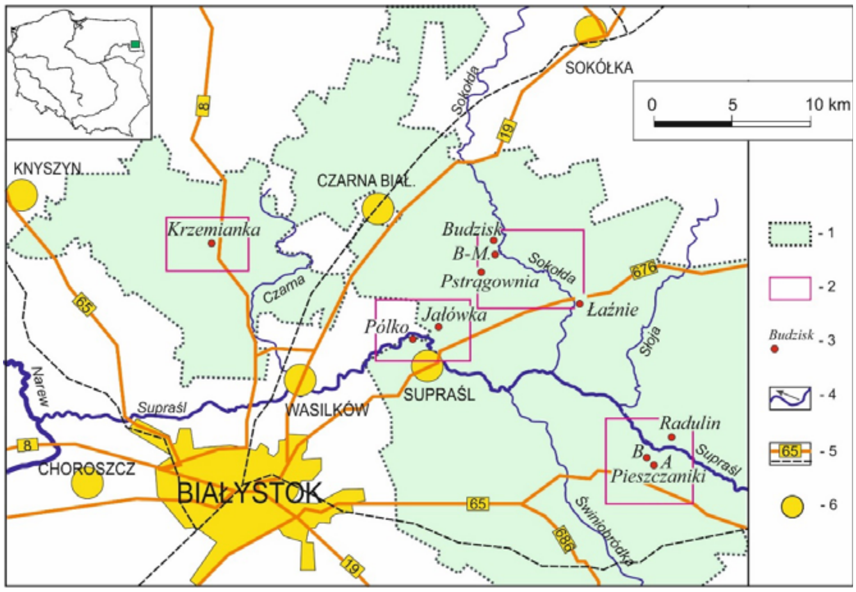

Fig. 1. Location of the selected spring-heads in the borders of the Knyszyńska Primeval Forest; *1* = the terrains of the Knyszyńska Primeval Forest, *2* = research areas, *3* = spring-heads, *4* = rivers, *5* = roads and the railways, *6* = cities and towns, B-M. = Budzisk-Migówka spring-head; source: own elaboration

The results of the aquifer granulometric analyses were compiled in Excel spreadsheet and grain size distribution curves were drawn using probability scale. Based on the granulometric analyses results, the filtration coefficient (*k*) was calculated. Hazen and USBSC (American) empirical models were used, according to the characteristics of aquifers. The results allowed to determine the conditions of groundwater migration in the exfiltration zones.

The tachymetric measurements and Digital Elevation Model from Lidar (ID resource material: PL.PZGiK.205, average error of height difference 0.2 m, density of points ranges from 4 to 12 points per m^2) [CODGiK 2017] allowed to prepare the detailed hipsometric maps of spring--head areas (except Jałówka and Radulin objects). In order to further analyse the alcove morphology, the enhanced terrain maps were created using hill-shading techniques and 3D models in Surfer 12.0.

STUDY AREA

Selected spring-head areas are located in the central and eastern part of the Knyszyńska Primeval Forest (Fig. 1), in the mesoregion of Białostocka Upland [KONDRACKI 2009]. They represent geomorphologically various areas. The analysed spring-heads were mostly developed in fluvioglacial, less often in glacial, fluvial or denudation forms (Tab. 1). Krzemianka, Budzisk, Budzisk-Migówka, Pstrągownia A and Pstrągownia B and Pieszczaniki occupy the outskirts of melt-out parts of valleys, typical for the Knyszyńska Primeval Forest [BANASZUK 1995; MICUN 2014], Łaźnie, Pólko and Jałówka occupy the slopes of river valleys, Radulin is located in edge of the terrace.

They are concentrated in 4 regions. The first is located in the middle course of the Sokołda River. It includes the spring-heads Budzisk (N 53°16’52.6”, E 23°22’25.6”), Budzisk-Migówka (N 53°16’42.4”, E 23°22’31.4”), Pstrągownia (N 53°16’30.6”, E 23°21’31.2”) and Łaźnie (N 53°14’38.6”, E 23°29’16.3”). The water from them is drained by the right tributary of the Sokołda River – the Migówka River. The spring-head Łaźnie is located on the eastern bank of the valley near Sokołda village. It is a limnokren [JEKATIERYNCZUK-RUDCZYK 2002; 2010]. These spring-heads reach a discharge volume of 1.7 dm^3·s^{-1} to 9.9 dm^3·s^{-1} [JEKATIERYNCZUK-RUDCZYK 2002; 2010; ŁOSZEWSKI 1984].

The second area of spring-heads concentration is located in the upper part of the Supraśl River catchment area near the villages of Radulin and Pieszczaniki (Fig. 1). The Radulin object (N 53°09’36.8”, E 23°34’27.2”) is located on the right bank of the Supraśl River and the small Radulinka tributary is leading the water out into the main watercourse. Pieszczaniki A (N 53°08’14.1”, E 23°33’5.8”) and Pieszczaniki B (N 53°08’22.8”, E 23°32’57.2”) are located on the left bank of the Supraśl River. They are drained through the Mielnica watercourse [ŁOSZEWSKI 2000]. These are morphologically very diverse objects. The discharge volume of the spring-heads in Pieszczaniki A is about 40 dm^3·s^{-1} [JEKATIERYNCZUK-RUDCZYK 2002; ŁOSZEWSKI 1984].

The third area is the part of the Supraśl valley near Supraśl town. The spring-head in the Jałówka Reserve (N 53°14’04.7”, E 23°20’38.4”) and the spring-head Pólko (N 53°13’17.5”, E 23°18’2.9”) at the left bank of the Supraśl River were studied. The last object is located about 15 km North of Białystok city in the Krzemianka Reserve (N 53°16’57.1”, E 23°07’05.7”) on the left bank of the Krzemianka river valley. The spring-head is located 200 m to the West of the national road No. 8. The average discharge volume of the spring-head is 10.1–10.9 dm^3·s^{-1} [JEKATIERYNCZUK-RUDCZYK 2002; 2010], 15.9 dm^3·s^{-1} [ŁOSZEWSKI 1984].

All the objects are located in the Supraśl River catchment. The spring Pólko is the only one where the water flows directly to that river. The rest go to the first-order tributaries, and from the Krzemianka to the second-order tributary. These are low-efficient or medium-efficient springs.

Table 1. Geomorphological, geological and hydrogeological features of the studied objects located in Białostocka Upland

Object	Geomorphological unit	Geological structure	Aquifer
Budzisk	slope of the valley	colluvial sands and silt sands	groundwater level at 144.5 m a.s.l., Quaternary level, good isolation, well efficiency >70 m^3·h^{-1}
Budzisk-Migówka	meadow terrace	sands and fuvioglacial gravels	groundwater level at 139.2 m a.s.l., Quaternary level, good isolation, well efficiency >70 m^3·h^{-1}
Pstrągownia	meadow terrace	sands and fuvioglacial gravels	groundwater level at 143.5 m a.s.l., Quaternary level, good isolation, well efficiency >70 m^3·h^{-1}
Łaźnie	slope of the valley	glacial sands and gravel with boulders	groundwater level at 134.5 m a.s.l., Quaternary level, no isolation, well efficiency 50–70 m^3·h^{-1}
Jałówka	slope of the valley	colluvial sands and silt sands	groundwater level at 133.0 m a.s.l., Quaternary level, good isolation, well efficiency 50–70 m^3·h^{-1}
Krzemianka	frontal moraine, kame	glacial sands and gravel with boulders, frontal moraine boulder till	groundwater level at 143.5 m a.s.l., Quaternary level, good isolation, well efficiency >70 m^3·h^{-1}
Pólko	slope of the valley	sands and fuvioglacial gravels	groundwater level at 120.5 m a.s.l., Quaternary level, no isolation, well efficiency 50–70 m^3·h^{-1}
Radulin	bottom of the valley	sands and humus sands, bottom of the valley alluvium	groundwater level at 134.5 m a.s.l., Quaternary level, no isolation, well efficiency 50–70 m^3·h^{-1}
Pieszczaniki A and B	bottom of the valley	sands and humus sands, bottom of the valley alluvium	groundwater level at 138.0–139.0 m a.s.l., Quaternary level, no isolation, well efficiency >70 m^3·h^{-1}

Source: own elaboration based on LASKOWSKI [1999; 2000]; KNYSZYŃSKI *et al*. [2004]; MADEJSKA and MADEJSKI [1998a, b].

The whole area of the Knyszyńska Primeval Forest is located in the area of the early-glacial relief that was formed in time of Warta Glacial deglatiation [BANASZUK 1995; LASKOWSKI 1999; 2000; MUSIAŁ 1992]. The studied spring-head areas are associated with the valleys of the main rivers of Supraśl, Sokołda and Czarna. These valleys have developed among the forms of glacial accumulation and fluvioglacial erosion and accumulation. Rivers have used outwash valleys and meltout depressions as their valleys connecting them with narrow water gaps [BANASZUK 1995; MICUN 2014].

Budzisk and Łaźnie spring-heads are located in the middle course of the Sokołda River. Its valley runs through extensive meltout depressions [BANASZUK 1995]. The highest culmination around the meltout depressions are formed by kame and dead-ice moraine hills. They rise up to 25 m above the present bottom of the valley (Borsucza Góra 160.6 m a.s.l.). They are made of sand and gravel, occasionally including boulders (Fig. 2). The wavy ground moraine made of glacial sands with addition of gravel with boulders stretches in the hinterland of these hills. It rises about 10–15 m above the bottom of the valley and falls towards it with a clear slope. In many places, the slope is cut by denudation valleys whose length ranges from almost 200 to almost 800 m, and the depth reaches 15 m. The bottom of the valley and the footslope are covered with colluvial sands and silt sands. In the vicinity of Budzisk almost a 300 m wide belt of fluvioglacial deposits is adjacent to the flanks of kames and moraines. The deposits were created during meltwater outflow. The surface of the deposits gently descends towards the centre of the depression. The bottom of the depression is filled with peaty deposits on fluvioglacial or meltout sands and gravels and Holocene alluvial sands. Meltout loamy sands appear in the higher parts of the bottom.

Geomorphology and lithology in Krzemianka and Jałówka are similar to Budzisk and Łaźnie spring-heads. The valleys' bottoms are filled with the fluvioglacial sands and gravels. They are the remnants of the meltwater outflow. There is a thin layer of Holocene alluvial deposits and occasionally peat spots. Culminations on the slopes of the valley are kames and dead-ice moraine hills reaching over 20 m of relative height. They have sand and gravel structure. In Krzemianka, a very characteristic feature is a large share of flint and its accumulation in the upper parts of the hills. In Jałówka, the steeper western slope is built of gravels and sands of esker. It is a fragment of Świętojański Esker [BANASZUK 1995; MUSIAŁ 1992]. On both sides there are numerous denudation valleys. Their bottoms are covered with silt sands.

The geomorphology and the lithology of Pieszczaniki and Radulin spring-heads are different. The bottoms of the post-glacial depressions are filled with the silts, sands and the sands with the post-glacial gravel. Lower depressions are formed by the Holocene sands with humus interbeddings and alluvial deposits. The West side of the depression is filled with fluvioglacial sands and gravels, which accumulated between dead-ice and already existing kame hills [KUREK, PREIDL 2004]. They form a kame terrace rising about 7 m above the bottom of the depression. Kame mounds and hills rise around the melt-out depression and their relative height is up to 40 m in the East. They are

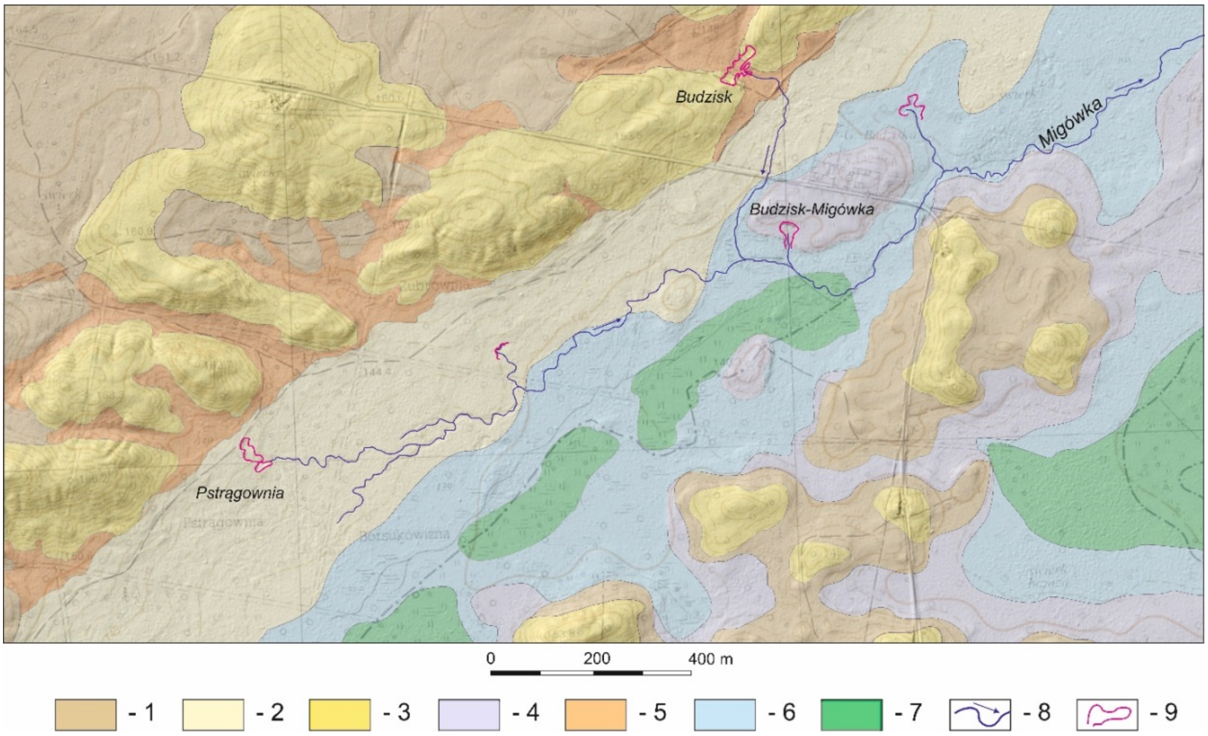

Fig. 2. Geological structure of Budzisk area (the Knyszyńska Primeval Forest), expanded the Warta Glaciation: *1* = ground moraine glacial sands and gravels with boulders, *2* = fluvioglacial sands and gravels of outwash plains and outwash valleys, *3* = sands and gravels of kames, *4* = sands of meltout depressions; the Pleistocene/ the Holocene: *5* = colluvial sands and silt sands; the Holocene: *6* = peaty deposits on fluvioglacial sands and gravels on the bottoms of valleys, *7* = peat, *8* = watercourses, *9* = spring-head alcoves; source: own elaboration based on LASKOWSKI [2000] and Geoportal [2017]

built of different sands and silts of various granulation. The southern bank of the melt-out depression is closed by a fragment of Świętojański Esker, rising 65 m above the bottom of the depression, along with the adjacent kame terrace. It creates a powerful alimentation area for underground waters outflowing in the area of Pieszczaniki.

RESULTS AND DISCUSSION

MORPHOLOGY OF THE STUDIED SPRING-HEADS AND MORPHOMETRY OF THE ALCOVES

The studied forms, despite their small size, stand out of the early-glacial landform of the Knyszyńska Primeval Forest. The largest of the studied spring-heads cover an area of over 0.4 ha. These are Pieszczaniki A (4320 m^2) and Pieszczaniki B (5700 m^2). Within these depressions there are distinct alcoves (Pieszczaniki A – 4 alcoves, Pieszczaniki B – 5 alcoves), whose individual surfaces range from 413 to 1480 m^2. Accordingly, they can be treated as individual forms. The average surface area of the investigated alcoves equals 1127 m^2 (Tab. 2, Fig. 3). The largest areas are Budzisk (2730 m^2), Krzemianka (2017 m^2) and Pstrągownia (1995 m^2). The smallest object is Pólko with less than 100 m^2. The ratio of the bottom surface to the entire alcove is between 0.3 and 0.87, and the average is 0.54. This means that the share of slopes in relation to total area of the alcoves may exceed 2/3 (Pieszczaniki A, W and E alcove) and on average it reaches half of the total area. When analysing the shape of the alcove, the perimeter to surface area ratio of the bottom of the alcove is from 0.15 to 1.62, an average 0.35. Such values indicate the generally compact nature of the alcoves.

The maximum length of the entire alcove reaches 93.9 m (Budzisk). The average length of the bottom of the alcoves is 51.6 m and is usually in the range of 40–60 m (in over half of the cases). The maximum width of the bottom is in the range of 10.2–72.3 m. Most often, however, it ranges from 20 to 30 m (in over 36% of the cases). The ratio of the maximum length to the maximum width of the bottom of the alcove is from 0.57 (Radulin) to 3.97 (Pstrągownia), an average of 1.97. Values smaller than 1 occurred in three alcoves (Pólko, Pieszczaniki B, Radulin), located in the bottom of the valley in the immediate vicinity of the watercourse. Other alcoves are elongated and the direction of elongation corresponds to the direction of the outflow. Elongation of forms is confirmed by the low values of Horton's index (an average value of 0.42 – Tab. 2).

An important element in the morphology of spring-head alcove is the slope closing the alcove. The height of

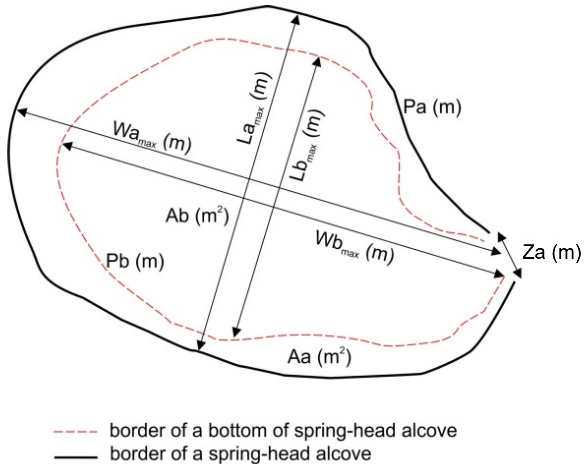

Fig. 3. Selected morphometric parameters of spring-heads alcoves; *Aa* = surface area of an alcove, *Ab* = surface area of a bottom, *Pa* = perimeter of an alcove, *Pb* = perimeter of a bottom, Za = alcove opening width, Wa_{max} = max. width of an alcove, Wb_{max} = max. width of a bottom, *La* = length of an alcove, *Lb* = length of an bottom; source: own study

Table 2. Morphometric parameters of the studied spring-head alcoves in the Knyszyńska Primeval Forest

Spring-head parameter	Symbol/formula/unit	Statistical parameter (*n* = 17)			
		min.	max.	mean	*SD*
Spring-head alcoves					
Surface area of an alcove	*Aa* (m^2)	98.0	2 732.3	1 126.6	673.0
Perimeter of an alcove	*Pa* (m)	45.0	343.8	162.5	65.1
Length of an alcove	*La* (m)	10.3	93.9	51.6	23.6
Max. width of an alcove	Wa_{max} (m)	15.5	86.0	33.6	15.7
Height of the slope closing the alcove	*Hs* (m)	0.6	3.6	1.5	0.8
Max. inclination of an alcove's slope	Sa_{max} (°)	15	40	25	7.2
Alcove opening width	*Za* (m)	1.3	56.5	7.1	13.0
Bottoms of spring-head alcoves					
Surface area of a bottom	*Ab* (m^2)	47.5	1 264.3	611.9	368.9
Perimeter of a bottom	*Pb* (m)	63.1	285.6	143.5	56.0
Max. length of a bottom	Lb_{max} (m)	7.0	85.4	45.3	20.8
Max. width of a bottom	Wb_{max} (m)	10.2	72.3	25.8	14.3
Perimeter to surface area ratio	*Pb*/*Ab* (–)	0.15	1.62	0.35	0.34
Max. length to max. width ratio	Lb_{max}/Wb_{max} (–)	0.57	3.97	1.97	1.05
Average inclination of a bottom	*Sbx* (°)	0.4	4.4	1.1	1.0
Horton's shape index	$Cb = Ab/Lb_{max}^2$ (–)	0.09	1.64	0.42	0.39
Max. width of a bottom to height of alcove's slopes ratio [BADURA *et al.* 2003]	$Vf = 2\ Wb_{max}/\ [(Hl - Ha) + (Hr - Hd)$ (–)	9.8	52.4	25.3	11.0

Explanations: *Hl* = left slope height, *Hr* = right slope height, *Ha* = height of a bottom.
Source: own study.

these slopes of the analysed alcoves averages 1.5 m (form 0.6 to 3.6 m). The highest values of slopes occur at the spring-heads of Budzisk (3.6 m) and Krzemianka (3.1 m). It is a result of location these alcoves at the foot of kame slopes. The lowest ones were observed in Pieszczaniki B (0.6–1.4 m) and in Radulin (1.2 m), which can be explained by their location at the bottom of the valley, and the hydrogeological and lithological conditions – the presence of saturated fine-grained sands.

The characteristical feature of the spring-head slopes is their steepness, which clearly distinguishes them from surrounding landforms. The inclination of the slopes reaches values from 15° to 40°. The steepest slope has an alcove of Pstrągownia spring-head (25–40°). The inclination of the slopes is usually in the range of 20–30° and the average measurement value is 25°. For comparison, the inclination of the slope of the surrounding landforms does not exceed 15°, and usually does not reach 8°. The inclination of the spring-head alcoves' bottoms usually lies in the range of 0.4–4.4° (Pólko).

BOTTOM SEDIMENTS OF THE ALCOVES

The thickest deposits are found in the bottoms of the spring-head alcoves Krzemianka, Pstrągownia and Jałówka. The content of the stone and gravel fraction exceeds 60%, including fractions with a diameter above 40 mm more than 20% (Tab. 3). The concentration of coarse material is the result of removing finer fractions by filtering waters. The finer material occurs only in the bottoms of Pieszczaniki and Łaźnie. They are dominated by medium-grained and fine sands, whose content locally exceeds 90%. They are the result of the accumulative activity of waters flowing in the bottoms of alcoves. Main factors determining the type of sediments in the bottom of the alcove is the amount of water and the velocity of its flow. In alcoves with high flow, finer material is moved outside. At the foot of the alcove walls only narrow, up to 4 m wide belts of poorly sorted deposits remain, while the entire middle part of the bottom is covered with gravel-boulder erosional pavement (Fig. 4). This type of spring-heads includes: Pstrągownia, Budzisk and Krzemianka. In smaller and slower flowing spring-heads (Pólko and Radulin) colluvium covers almost full area of bottoms. Sedimentation conditions in the alcove's bottoms are modified by the presence of beaver dams and windthrow woods dams. This is the case in Budzisk-Migówka, Łaźnie (Fig. 4), and to some extend in Krzemianka and Jałówka. Fine sand and organic matter accumulate in the reservoirs. The bottoms of Pieszczaniki spring-head depressions are dominated by colluvial sediments and peat. The finer material is moved down the alcove. However, in the summer, rich vegetation keeps it within the depression. Some of the sediment is retained by the tree root system. As a result, the clumps surrounding the tree roots develop (Pieszczaniki A). In terms of origin, the deposits found in the alcoves can be described as fluvial, associated with the accumulation activity of water flowing in the bottom and its erosion, colluvial near the slopes, and organogenic.

Bottom sediments are sometimes modified by windthrow erosion and zoogenic and anthropogenic processes. The storm of 17th June 2016, in the alcoves of Budzisk and Jałówka, resulted in creating openings that changed the shape of the alcoves and the surface of their bottom. The deposits in the bottom were disturbed and mixed. The role of windthrow erosion in transforming spring-head alcoves in the mountains was pointed out by WROŃSKA [2006a, b]. Beaver dams closing alcoves cause the formation of sedimentation basins (Krzemianka, Budzisk-Migówka). There is an accumulation of loamy sands and sands with humus

Table 3. Granulation and the filtration coefficient of the analysed spring-head alcoves

Object	Percentage of particle of specified diameter in mm (%)							Filtration coefficient (m·d^{-1})	
	>40	2–40	0.5–2.0	0.25–0.5	0.1–0.25	0.02–0.1	<0.02	USBC	Hazen
Krzemianka 1	0.0	24.7	33.3	19.1	10.4	7.3	5.2	8.6	2.3
Krzemianka 4	21.8	38.9	16.9	15.2	6.7	0.5	0.0	44.6	33.6
Krzemianka 6	0.0	27.1	39.3	20.2	11.1	2.0	0.3	21.0	17.6
Krzemianka 7	0.0	21.1	26.5	23.9	21.4	5.8	1.4	6.8	4.8
Krzemianka 8	0.0	10.7	25.9	35.9	22.5	4.1	0.9	8.6	13.5
Łaźnie 1	20.8	10.9	31.9	27.8	7.2	1.1	0.3	22.6	69.1
Łaźnie 2	0.0	19.9	43.4	25.0	8.6	2.2	0.8	21.0	38.7
Łaźnie 5	15.4	47.1	19.3	14.4	3.4	0.4	0.0	72.2	41.0
Łaźnie 6	0.0	3.6	25.9	49.1	19.1	1.7	0.6	9.6	28.9
Łaźnie 7	0.0	3.1	27.9	46.6	18.6	2.9	1.0	9.6	25.9
Pólko 1	0.0	0.2	1.2	17.4	72.8	7.1	1.3	2.4	8.8
Pieszczaniki A 1	5.5	49.8	16.7	18.5	9.4	0.1	0.0	33.6	42.3
Pieszczaniki A 2	0.0	34.8	24.6	23.6	15.5	1.2	0.3	16.6	16.0
Pieszczaniki A 3	0.0	1.8	15.8	38.8	40.9	2.3	0.5	6.8	12.5
Pieszczaniki A 4	0.0	0.3	11.7	34.3	51.3	2.3	0.0	5.3	11.5
Pieszczaniki B 1	0.0	1.4	3.8	11.6	69.1	12.1	2.1	1.9	6.2
Pstrągownia 1	0.0	14.0	16.6	48.6	16.1	3.6	1.1	12.8	28.9
Pstrągownia 2	24.0	10.9	6.3	44.2	13.3	1.3	0.0	15.3	35.3
Pstrągownia 3	5.6	15.0	15.5	43.5	17.5	2.6	0.2	12.8	25.9
Pstrągownia 4	20.0	32.3	10.6	23.4	12.1	1.5	0.1	19.5	17.6
Pstrągownia 5	0.0	0.1	0.9	25.9	65.4	7.2	0.6	2.4	13.7

Source: own study.

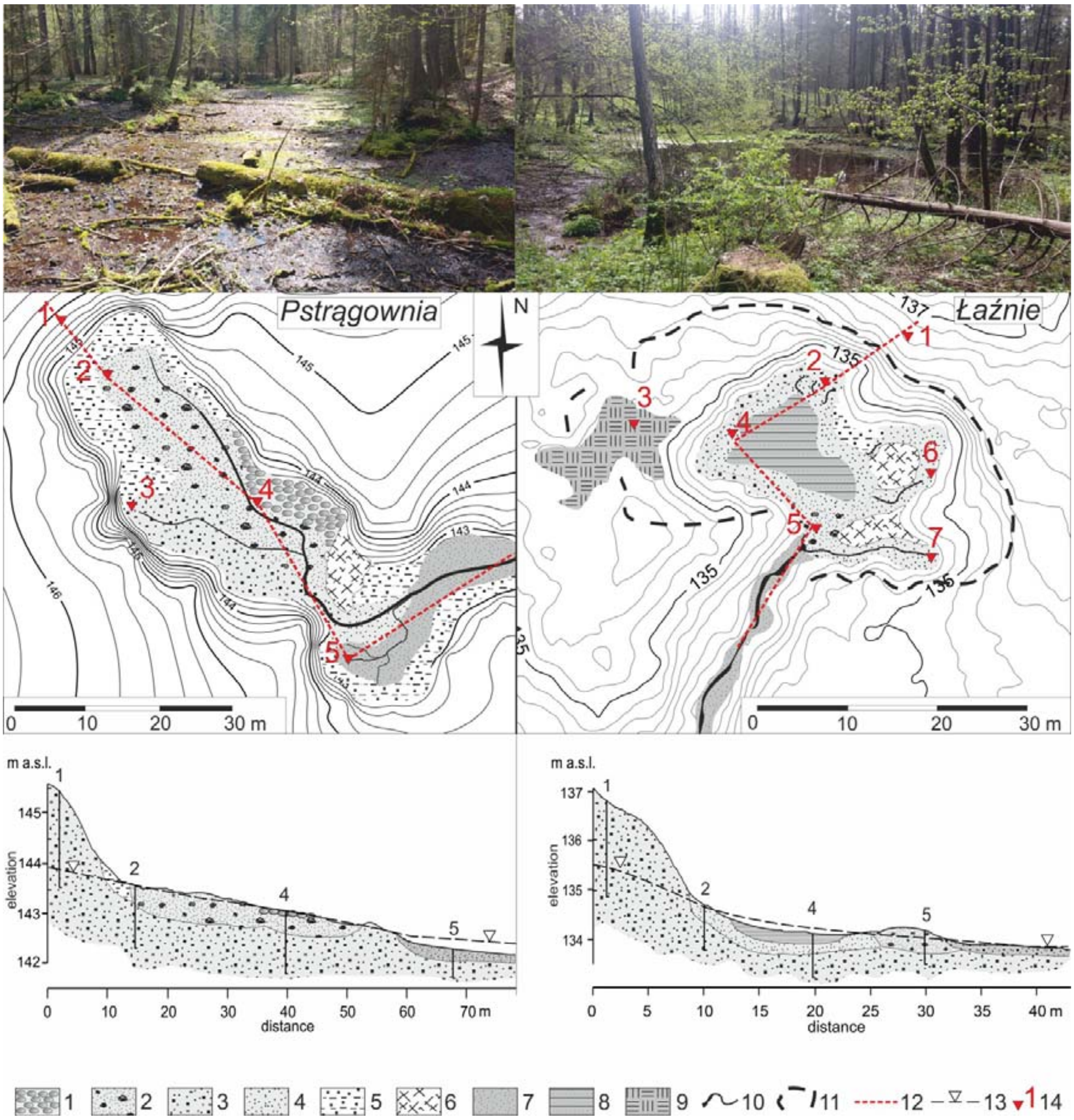

Fig. 4. The bottom deposits in the Pstrągownia and Łaźnie spring-head alcoves; *1* = gravel-boulder erosional pavement, *2* = gravel with stones, *3* = medium sand with gravel, *4* = medium sand, *5* = colluvial sand of mixed grain size, *6* = deposits of the clumps and spurs, *7* = alluvial, fine=grained sand, *8* = fine-grained lake deposits with organic material, *9* = peat, *10* = watercourses, *11* = old edge of the alcove, *12* = cross section, *13* = watertable, *14* = samplings; source: own study

interbeddings whose thickness sometimes exceeds 0.5 m. When the water fills the entire alcove, the groundwater erosion processes cease. Scouring of the slopes leads to the intensification of abrasion and slope processes. The bottoms of the Pieszczaniki A and Pieszczaniki B spring-head depressions have been transformed anthropogenically. As a result of deepening drainage and excavating a pond with an area of more than 1000 m^2 in 2002, linear erosion appeared along the waterways intensifying breaking and collapsing unstabilised edges.

AQUIFER GRANULOMETRIC ANALYSIS

The aquifers of the studied springs of the Knyszyńska Primeval Forest are characterised by high variability of granulometric composition, often within one spring-head depression. The thickest aquifers occur in Krzemianka and Pstrągownia. The content of gravel is over 20% (Tab. 3). The content of sand grains (0.1–2.0 mm) in aquifers varies from 62.8% (Krzemianka) to 97.4% (Pieszczaniki A 4). An average sand content is 68–82%. Fine particle admixtures rarely exceed 10% (Krzemianka 1.0–12.5% and Pieszczaniki B 1 – 14.2%). Mostly they are grains with a diameter of 0.063–0.1 mm, so often referred to as very fine sand [URBANIAK-BIERNACKA 1978]. Therefore, it must be stated that the basic aquifer in the examined springs are sands with gravel and sands of glacial, fluvioglacial and fluvial origin.

Analysis of grain size distribution curves mainly indicates the low degree of material selection (Fig. 5). Exceptions are fluvial and fluvioglacial sand deposits found in the samplings of Pstrągownia 5, Pieszczaniki B 1 and Pólko 1. The grains of fine sand (0.1–0.25 mm) predominate in them and their content exceeds 65%. The high coef-

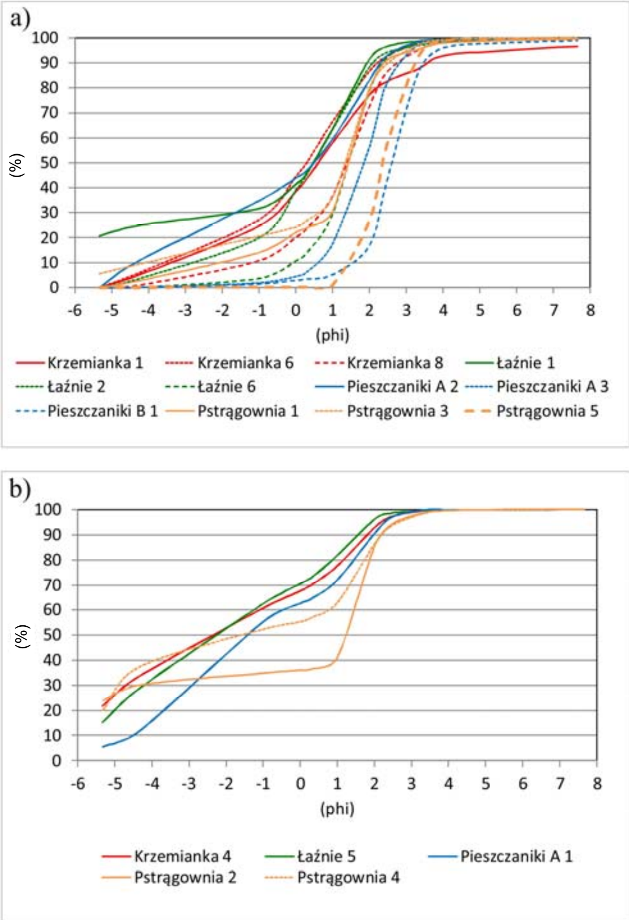

Fig. 5. Grain size distribution curves of the deposits of the selected spring-head alcoves in Knyszyńska Primeval Forest: a) aquifer deposits, b) bottom deposits; source: own study

ficient of graining non-uniformity, up to 60, confirms the low selection of material. This fact has a positive influence on the filtration properties of aquifers. The filtration coefficient was calculated for the studied objects and reaches values from below 1.9 to 72.2 m·d^{-1} (USBSC formula – American) or from 2.3 to 69.1 m·d^{-1} (Hazen formula). It is worth noting that there is considerable variation in the value of the filtration coefficient within a single spring-head. In Krzemianka the filtration coefficient reaches values from 2.3 to 44.6 m·d^{-1}, in Łaźnie from less than 10 to over 72 m·d^{-1}, in Pieszczaniki A from 5.3 to 42.3 m·d^{-1}, in Pstrągownia from 2.4 to 35.3 m·d^{-1}.

DEPENDENCE OF SPRING-HEADS MORPHOLOGY FROM GEOMORPHOLOGICAL AND LITHOLOGICAL CONDITIONS

The examined spring-heads in terms of location in relation to the terrain forms can be divided into subslope and riverbank [MONIEWSKI 2007]. Subslope forms: Pstrągownia and Krzemianka are characterised by narrow alcoves, strong elongation and high and steep slopes that clearly distinguish themselves from the bottom (Fig. 6). The L:W ratio is the highest, exceeds 3.5, and the shape index is low (Tab. 2). In terms of morphometric characteristics, they are similar to spindle-shaped alcoves [MAZUREK 2010], but unlike the described Pomerania alcoves, there are no denudation valleys or gullies. Their elongated shape is related to seepage erosion, which is the fastest around the main groundwater outflow in the alcove. The main role of the seepage erosion in the formation of spindle-shaped alcoves is also depicted by MONIEWSKI [2004] for the upper course of Moszczenica River in the northern part of Łódź Hills. The slopes closing the alcoves are formed by intensive headward erosion, breaking and collapsing.

The different morphology is represented by the Budzisk-Migówka and Łaźnie alcoves, whose overall outline is oval, longitudinal axis is almost equal to the width and L:W ratio is below the average. At the same time the shape index is from 0.23 to 0.55, and the elongation index of the bottom [SCHUMM 1977] is 0.55 and 0.84. These results are similar or identical to those obtained for the bowl-shaped alcoves [MAZUREK 2010]. In this case, the main factor modifying the shape of the alcoves seems to be varied by lithology of the substrate. It is not possible to exclude stronger headward and seepage erosion in the places of water exfiltration, so that the alcove expands in some directions faster than the others. Landsliding of the fine deposits is one of the reason of creating the clumps. This is confirmed by the presence of a separated clump at the slope closing the alcove (Fig. 6). There is also the accumulation process of fine sand with organic material in the bottom of these alcoves.

The spring-heads of Pólko, Radulin and Pieszczaniki A (eastern alcove) have L:W ratios below 1. The longer axis is the one perpendicular to the direction of the runoff of water from the alcove. These are smaller objects, wide open towards the watercourse. They are similar to basin-shaped alcoves [MAZUREK 2010], but have significantly higher values of the bottom extension index (from 0.95 to 1.44) and the shape index (from 0.71 to 1.64). In this case, the main factor that modifies the shape of the alcove is the erosive activity of river water (lateral erosion), which manifests itself by elongating the axis parallel to the course of the river.

The use of the indicator: the maximum width to height of the slope allows for the identification of shallow alcoves with broad bottom (high index values) and deep and narrow alcoves [BADURA *et al*. 2003]. In the examined alcoves, this index ranged from 9.8 to 52.4. The obtained values allow to classify almost all alcoves as shallow and wide. For comparison purpose, the average value of this indicator, calculated for Parsęta spring-heads in late-glacial areas, was 4.69, and the alcoves were considered to be deep and narrow [MAZUREK 2010].

Spring-head depressions of Pieszczaniki form a morphologically separate group (Fig. 6). Their characteristic feature is strong fragmentation. Individual alcoves are separated by clumps and small ridges reaching 1.2 m. These alcoves are irregularly shaped and their short, low slopes reach 1.5 m. The morphometric indicators are close to the average values (Tab. 2). These slopes experience a great activity of both slope and erosion processes. The spring-head depressions of Pieszczaniki, could be described as dendritic drainage patterns.

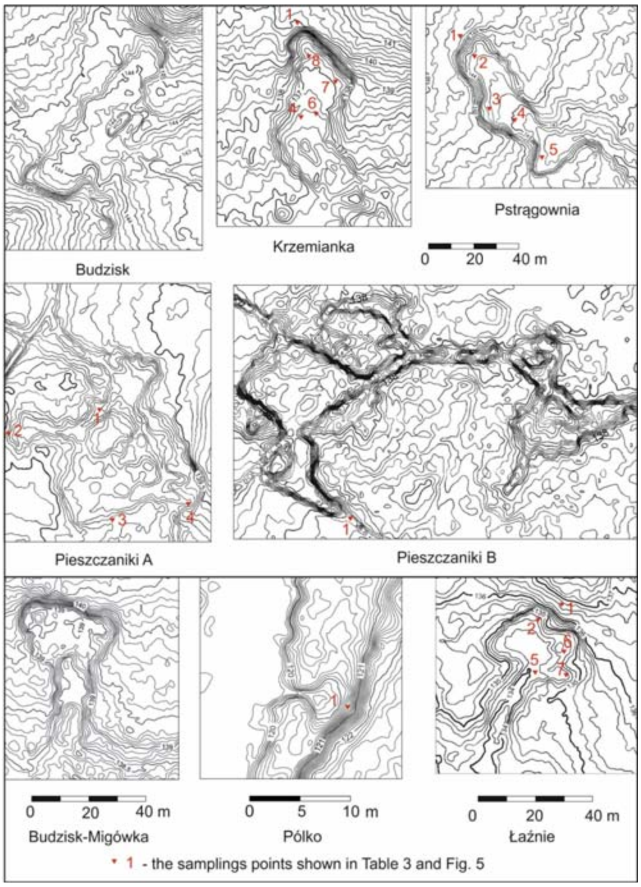

Fig. 6. Contour maps of selected spring-head alcoves; source: own study

Specific features of the morphology of the depressions and spring-head alcoves of Pieszczaniki are the result of lithological conditions. Sands dominate in that area, sometimes exceeding 95%. It is also important that the share of medium sands (0.25–0.5 mm) and coarse sands (0.5–2.0 mm) reaches 50% of the total volume. For this reason the filtration coefficients are relatively high (from 2 to over 30 $m \cdot d^{-1}$), which guarantees swift filtration of groundwater. At the same time, the dominance of sand deposits in the bottom of the valley and the lower part of the slopes (kame sands and silts, kame terrace sands) facilitates the transport of material with a relatively small grain size. Gravel, glacial and fluvioglacial deposits of Budzisk, Pstrągownia, Jałówka or Krzemianka spring-heads are not so vulnerable to erosion and transport by exfiltration waters. The slopes of the depressions remain longer in balance and the inclination of the scarps is higher. Landsliding, breaking and collapsing prevailes on the slopes of the alcoves. Accumulated colluvial deposits are not transported outside the alcove and cause the formation of subslope wetlands. This process was also described by CHOMUTOWSKA and KRYJAN [2014]. In the central parts of the alcoves, in places of greater underground water exfiltration and faster flow, finer grains are washed out. As a result, residual accumulations of gravel and stones remain in the bottom. This is indicated by the displacement of the grain size distribution curves of the bottoms to the coarser fractions in proportion to the bottom sediments and aquifers (Fig. 5). Such dependence for bottom sediments of the spring-heads in the Parsęta catchment was determined by MAZUREK [2010].

CONCLUSIONS

The values of morphometric indicators obtained in the early-glacial area are similar to those calculated in the late-glacial terrains. Based on the analysis of morphometric characteristics, in terms of shape, examined alcoves were classified as basin-shaped, bowl-shaped and spindle-shaped. Different morphological proseses prevail in each of these types. In the case of basin-shaped alcoves lateral erosion is dominated. Bowl-shaped alcoves are formed mailny by seepage erosion, landsliding and accumulation in the bottom, while in spindle-shaped alcoves we can observe domination of seepage erosion, headward erosion, breaking and collapsing. Dendritic drainage pattern spring-head depressions not yet recognized by other authors were also distinguished.

The investigated alcoves have varied mineral and mineral-organic deposits. In the most cases, coarse deposits are dominated, mainly gravels and stones, with sand admixture. Locally occurring peat is a remnant of the earlier bottom of the depression. In individual parts of the alcove there is a variability of the aquifer granulation from fine and medium sand to coarse gravel with sand admixture. The calculated filtration coefficients are from 1.9 to 72.2 $m \cdot d^{-1}$. The lithological variation of aquifers in the spring-heads directly affects the rate of groundwater filtration in different parts of the alcoves, which in turn leads to different morphogenetic processes and results in changes in the morphology of the spring-head alcoves. The presence of coarse-grained deposits promotes the formation of spindle-shaped alcoves. In the case of finer materials the shape of creating alcoves is depend on the morphological processes.

The use of combined tachymetric methods and Digital Elevation Model for krenological and geomorphological charting allowed to obtain a detailed picture of the morphology of spring-head alcoves in the Knyszyńska Primeval Forest.

The results of this study expand insufficient knowledge about forming and features of spring-head alcoves in the Polish Lowland.

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Charakterystyka morfologiczna i uwarunkowania litologiczne źródlisk w Puszczy Knyszyńskiej

STRESZCZENIE

Celem opracowania było określenie cech morfologicznych wybranych źródlisk na terenie Puszczy Knyszyńskiej oraz rozpoznanie warunków litologicznych w miejscach wypływu wód podziemnych na powierzchnię. W trakcie badań przeprowadzono szczegółowe pomiary niwelacyjne terenów źródlisk. Do analizy morfometrii wykorzystano również wyniki pomiarów laserowych Lidar, pozyskanych z Centralnego Ośrodka Dokumentacji Geodezyjnej i Kartograficznej w Warszawie. Na podstawie danych stworzono w programie Surfer 12 szczegółowe mapy poziomicowe i określono podstawowe parametry morfometrii badanych źródlisk. W celu rozpoznania warunków litologicznych wykonano analizy granulometryczne, obliczono współczynnik filtracji utworów wodonośnych w poszczególnych źródliskach za pomocą wzorów empirycznych Hazena i USBSC. Ze względu na sytuację morfologiczną badane obiekty zaklasyfikowano do typów źródlisk podzboczowych, podstokowych i przykorytowych. Pod względem kształtu nisze źródliskowe zaliczono do typów nisz basenowatych, misowatych i wrzecionowatych. W każdym z tych typów dominują różne procesy morfologiczne. Nisze basenowate kształtowane są głównie przez erozję boczną, misowate przez erozję źródliskową, procesy osuwania i akumulacji dennej, natomiast w niszach wrzecionowatych dominuje erozja źródliskowa, wsteczna, obrywanie i odpadanie. Wyróżniono także układy dendrytyczne w zagłębieniach źródliskowych. W badanych wypływach wód podziemnych warstwy wodonośne stanowią piaski oraz piaski ze żwirem glacifluwialne o zróżnicowanym uziarnieniu. Najgrubsze frakcje budują warstwę wodonośną w obiekcie Pstrągownia, średnie uziarnienie mają wodonośce źródlisk Budzisk, Krzemianka i Łaźnie. Piaski drobno- i średnioziarniste stanowią warstwy wodonośne w obiektach Pólko i Pieszczaniki. Zmienność litologiczna utworów wodonośnych w źródliskach wpływa bezpośrednio na tempo filtracji wód podziemnych w różnych częściach nisz, co w następstwie prowadzi do różnego przebiegu procesów morfogenetycznych i skutkuje zmianami w morfologii nisz źródliskowych.

Słowa kluczowe: *morfologia nisz źródliskowych, Puszcza Knyszyńska, warstwa wodonośna, źródlisko*