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Secular and catastrophic processes reflected in sediments of the Suchedniów water reservoir, Holy Cross Mountains (Poland)

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Abstract

The Suchedniów water reservoir is located in the central section of the River Kamionka in the northern part of the Holy Cross Mountains of central Poland. This area once belonged to the Old Polish Industrial District that, during the Middle Ages, was very intensively developed by iron metallurgy. Many forges and mills along the rivers used water power, which led to the construction of an anthropogenic, small-scale water retention system. At the beginning of the twentieth century many of these reservoirs were drained after the collapse of metallurgical activities. The present-day reservoir was built in 1974 and drained in 2017. Research into the drained basin has documented various forms and sediments, some of which record present-day depositional processes (fire proof clay layer, inland fan delta), while others represent the historical period (lacustrine sediments of older reservoirs). Traces of catastrophic events have been preserved as well; an assemblage of megaripples marks the sudden drainage caused by a dam break in 1974.

Key words: sedimentology, lacustrine sediments, fan delta, megaripples, anthropogenic pond

1. Introduction

For many years lacustrine sedimentation has been a popular topic amongst numerous scientists, both in Poland (e.g., Wajda & Witkowski, 1985; Malkiewicz & Pazdur, 1995; Zieliński, 2014; Gierszewski, 2018; Żarczyński et al., 2019) and elsewhere (e.g., Gilbert, 1885; Moss, 1972; Tuttle et al., 1997; Bridge, 2003; Fleisher et al., 2003; Postma, 2003). The Old Polish industrial district is an example of such an area where this type of research can find excellent conditions.

The beginning of metallurgy in the Holy Cross Mountains dates back to the Roman period (Bielenin, 1993; Orzechowski, 2007); subsequent development during early mediaeval times was based on the use of hydropower. There were many forges and watermills in the Old Polish Industrial District area in the northern part of the Holy Cross Mountains (Przepióra et al., 2016). Those industrial objects were built near rivers, creating ponds as anthropogenic small-scale water retention systems (ASWRS) (Kalicki et al., 2019). This system is typical of many larger and smaller watercourses in the Holy Cross Mountains. The dismantling of these forges at the start of the twentieth century led to the disappearance of ASWRS. Where some of the old ponds had been, larger reservoirs were constructed (Kalicki et al., 2018a, b). An example is the Suchedniów water reservoir; this was constructed in 1974 in the central reaches of the River Kamionka, a right tributary of the River Kamienna, which is a small watercourse of about 17 km in length and a catchment area of 107 km^2. The area analysed is located in the northern part of the Świętokrzyskie Voivodeship, on the Suchedniów Plateau, which is part of the Kielce Upland (Kondracki, 1977, 2002), to the north of the main range of the Holy Cross Mountains (Fig. 1).

Climatological conditions of this area are based on data obtained from the Skarżysko-Książęce and Skarżysko-Kamienna rain gauges. Average annual precipitation at Skarżysko-Książęce during the period 1891–1930 was 600 mm, while during 1951–1990 this was 627 mm at Skarżysko-Kamienna (Żarnowiecki, 1996). In Suchedniów (1961–1990), the highest precipitation occurred from June to August and reached 653 mm per annum (Suligowski et al., 2009). In Skarżysko-Kamienna, the greatest average monthly precipitation was in July (89.0 mm), the smallest during February (32.2 mm). Heavy rainfalls occurred between May and August and are most often associated with storms near Suchedniów, with a maximum in July (14% of days) (Żarnowiecki, 1996).

The nearest hydrographic gauge station is at Bzin (co-ordinates 51°10'N, 20°86'E) on the River Kamienna. In the period 1951–2010, the average highest flow was 26.78 m^3/s, the average annual flow 1.82 m^3/s and average lowest flow 0.39 m^3/s (Raport wykonania map, 2013).

Data from the Wąchock hydrographic gauge station on the River Kamienna (co-ordinates 51°41'N, 21°01'E), in the period 1951–2000, record the highest flow from March to June, while in May the k-Parde flow coefficient (i.e., the ratio of mean monthly flow to mean annual flow) exceeds 157 k. The lowest level is at 64 k during November. The minimum acceptable flow is 0.76 m^3/s, while for individual

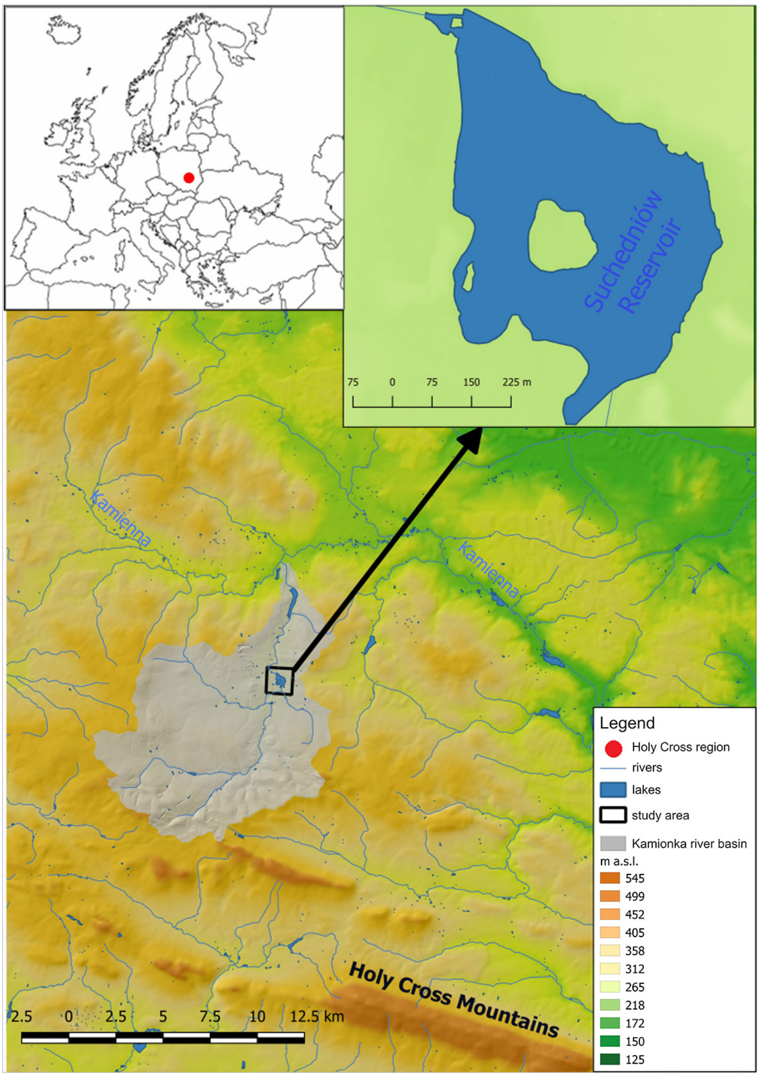

Fig. 1. Location of the study area in Digital Elevation Model

periods it is 0.29 m^3/s (winter), 0.43 m^3/s (spring), 0.24 m^3/s (summer) and 0.49 m^3/s (autumn) (see Suligowski et al., 2009).

The reservoir parameters analysed prior to hydrotechnical works in 2017 were 21.4 ha of the area and a capacity of 226,000 m^3 at an average depth of about 1 m. The catchment area of the reservoir closed by a dam is 83 km^2 (Bąk et al., 2012). The siltation significantly reduced the reservoir retention function. In 2017, the lake was drained for the first time since its flood protection potential was restored (Fig. 2A). The reservoir drainage enabled

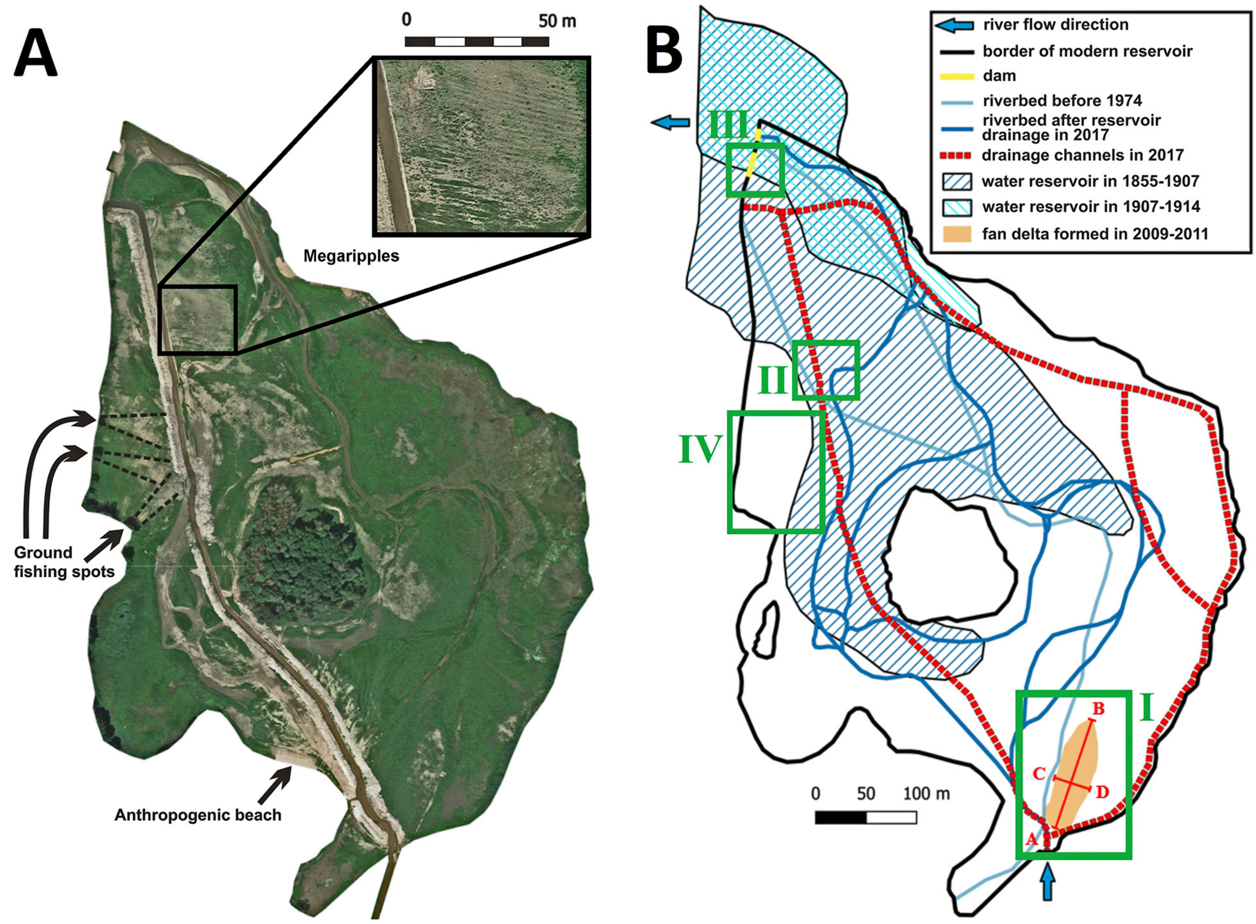

Fig. 2. A – Aerial photography; **B –** Situation map of the Suchedniów water reservoir: I – delta site, II – megaripples site, III – dam site, IV – fishing spot site

Fig. 3. Dry Suchedniów water reservoir (spring of 2017)

to carry out studies of sediments laid down in the reservoir for a period of almost 45 years, documenting their thickness, vertical and spatial variability and the formation of accumulation forms created in the lake. After drainage (Fig. 3), the hydrotechnical works started to restore its retention function works by deepening of the reservoir basin.

2. Aim of study and methods

The aim of the present research was to obtain data on the forms and sediments accumulated in the Suchedniów water reservoir, to capture the diversity of sedimentary environments in the basin and to document the sedimentation rate and role of natural and human processes in the fill-in of anthropogenic shallow reservoirs. This kind of study is very rare in the literature.

Field work was based on sections and shallow wells drilled by hand drill "Eijkelkamp" for compact and "Instorf" for loose deposits. The "COBRA" impact drill was used on the inland fan delta. In this way, sediments of an unchanged structure could be recovered for a proper structural and textural analysis.

The grain size of the material obtained was analysed using sieve and laser diffraction method by "Mastersizer 3000". Results were converted using the Folk-Ward's distribution parameters (Folk & Ward, 1957) in the "GRANULOM" programme. Based on these data, five lithological maps were prepared for 45 sections and shallow wells across the entire basin. Each map represents a different range of depths of accumulated deposits (up to 1 m). These materials have been developed using a QGIS programme, pH parameters have been analysed by Microcomputer Multifunction Meter CS-551, $CaCO^3$ by Scheibler's method. The results were used to prepare pH-scale maps for a different range of depths of the accumulated deposits.

The inaccessibility of wet areas in some parts of the reservoir has led to the irregular distribution and the shallow nature of hand-drilled wells. The effect of this is a lack of precision in some parts of the study area; thus, our presentation of results in graphical form are subjective.

3. Results

During the research, 45 sections across the entire study area were produced. These allowed the identification of sediments that accumulated in different parts of the reservoir. Thorough field analysis and results obtained made it possible to designate four distinct sites. These represent different sedimentary subenvironments in the Suchedniów water reservoir.

3.1. First site – Delta

The first site is located in the southeastern part of the reservoir basin (Fig. 2B) and represents inland delta deposits (Fig. 4) (Zieliński, 2014; Wang et al., 2015). Over the years, this part of the reservoir was intensely silted by sediments transported by the River Kamionka. Delta development started following regulation in 2005 of the river bed in the estuary section. An increase in delta accumulation rate (the youngest part of the delta) took place between

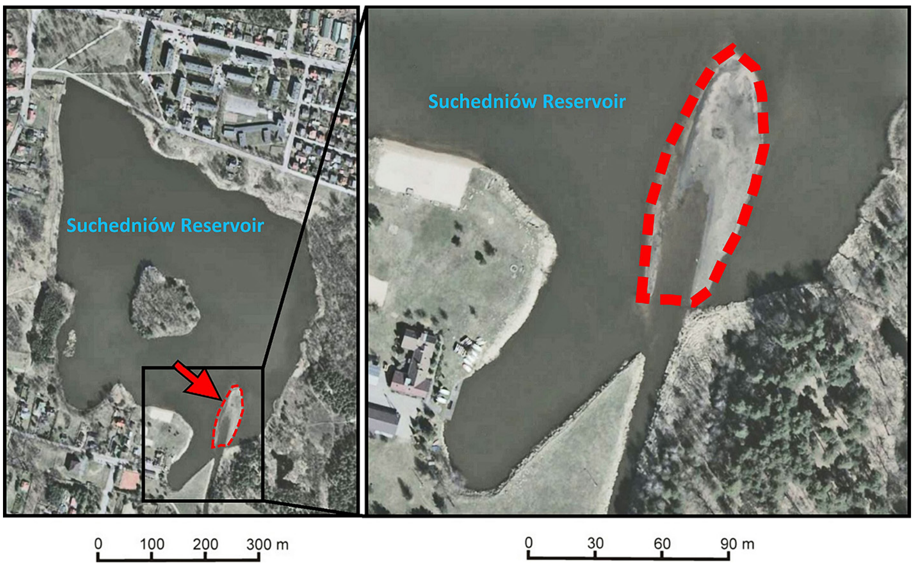

Fig. 4. The delta created in the estuary of the River Kamionka to the Suchedniów water reservoir (www.geoportal.gov.pl)

2009 and 2011. In this period, the River Kamionka supplied material from embankments of the S7 motorway that was constructed at the time (Bąk et al., 2012; Rzętała et al., 2013; Biesaga et al., 2018; Kalicki et al., 2018a, b). Those embankments were cut by the river that transported sediments and accumulated these in the reservoir basin. As a result of this process of redeposition from the river estuary to the lake, a clearly visible delta came into being. Over the following years, this form was expanded by additional material transported by the river until 2017, when hydrotechnical works were initiated and the reservoir was drained. The upper part of this form was above the water level before the hydrotechnical works started in the Spring of 2017 (Fig. 5).

The fan delta, with an estimated capacity of 3,882 m^3 and located at the estuary of the river to a reservoir, measures about 100 m in length and 40 m in width (Górski et al., 2012), comprising alternating fine and medium sands with a fine admixture (silt and clay) (3–45%). The average value matter of the whole delta: gravel (about 1%), coarse sand (about 3%), medium sand (about 16%), fine sand (about 45%), silt (about 24%) and clay (about 10%). Individual sediment layers vary from well to poorly sorted.

The structure of the fan delta is well visible in the sediments. The slope at the bottom of the fan delta is about 2° (dark, silty layers), in overlying sandy layers about 6–7° (Fig. 6). Many distinct erosional channel structures have been recognised in exploration pits. Channels reach a width and depth of 80–140 and 5–40 cm, respectively, and are filled with medium and fine sands (Fig. 7). A longitudinal cross section documents the delta formation phases with fine and coarser sediments accumulated by floods (Biesaga et al., 2018; Kalicki et al., 2018a, b).

Fig. 5. A – The delta in 2017, prior to reservoir drainage (photograph by S. Piasta); **B –** The delta in the same year, during hydrotechnical works

Fig. 6. Inclined beds of the subaqueous delta slope. The wall is concordant with palaeoflow and delta progradation. Lithofacies symbols: FSi – sandy silt with inclined stratification, Si – sand with inclined stratification, Sh – horizontally stratified sand

The delta formed during seven phases, as shown in a longitudinal section (A–B) (Fig. 8). At the beginning of each phase, the coarser sediments (sand with gravels, medium sand) were laid down and at the end of each phase, accumulation of finer material (silt and clay) took place. The delta can be divided into two units that differ from each other by deposit proportions and slope. In the lower unit three phases (I–III) are recorded. At the start, phase (I) saw accumulation of silty sand with gravels, medium sand and silty sand. Silty sand and silt were deposited at the end of this phase. In the second phase (II), medium sand and fine sand accumulated. The third phase (III) is represented only by deposition of medium sand. Deposits of phases I–III dip at about 10–30°.

The upper unit of the delta is differs markedly from the lower one. The dip is much greater (>20°), which may be indicative of a more dynamic environment and an increase of accumulation rate (e.g., flood in 2010). In the fourth phase (IV), vari-grained material was laid down. Deposition started from a

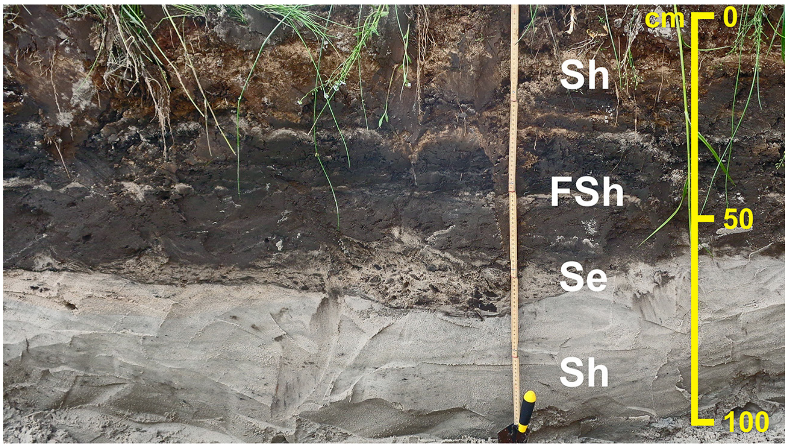

Fig. 7. Subaerial channel infills in the subaqueous delta (Se). Lithofacies symbols: Se – erosional trough infilled by sand with clasts, Sh – horizontally stratified sand, FSh – horizontally stratified sandy silt

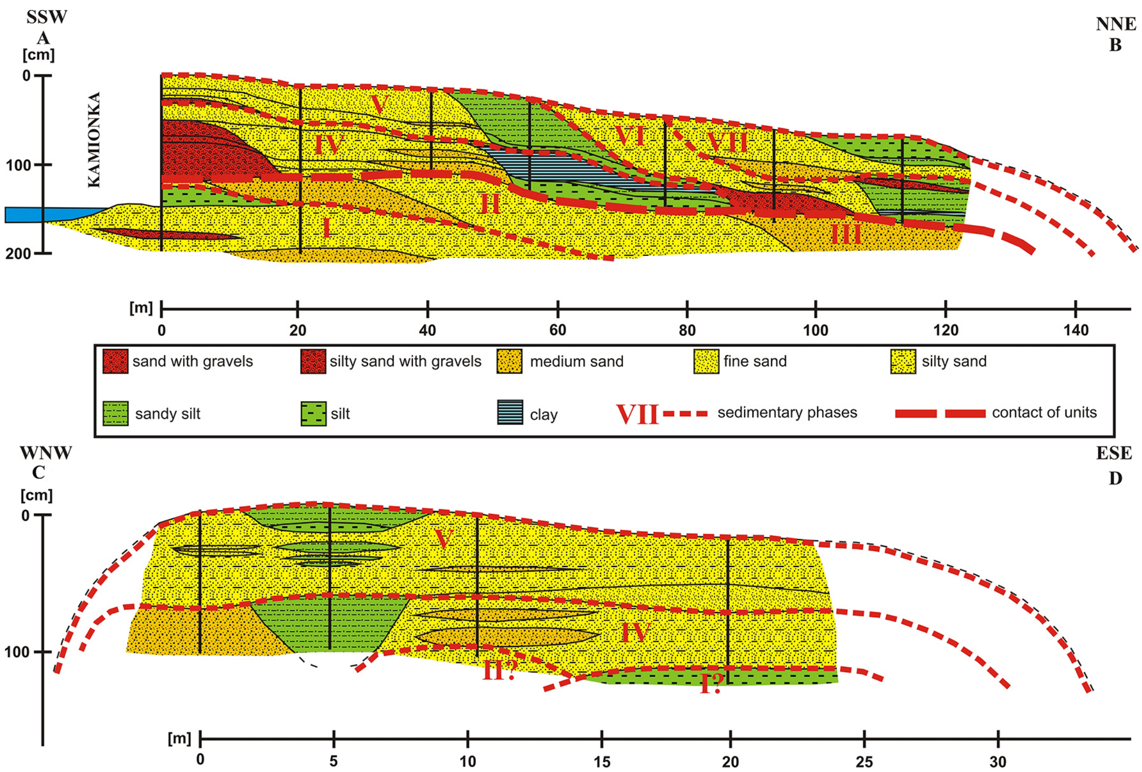

Fig. 8. The delta (first site): longitudinal (A–B) and transverse (C–D) cross sections. Deposits of successive sedimentary phases are marked by red dashed lines

thick layer of coarse material (sand with gravels and silty sand with gravels); fine sand, silty sand with medium sand intercalations occur above. The finest material (sandy silt, silt and clay) was deposited at the end of this phase. In the fifth phase (V), accumulation starts with sand with gravels, followed by fine sand as well as silty sand with intercalations of medium sand. Finally, sandy silt and silt were deposited. At the beginning of the sixth phase (VI), sands with gravels were laid down, followed by silty sand with a thin layer of medium sand. The deposition ends by settling of the finest sediment (sandy silt and clay). The last, seventh phase (VII), represents sediments accumulated furthest from the river estuary. In volume, the coarse- and medium-grained sediments (silty sand with gravels and medium sand) are lesser than fine material (silty sand, sandy silt and clay) that end this depositional phase.

The cross section C–D (Fig. 8) shows a predominance of finest deposits (fine sand, silty sand) with characteristic lenses of medium sand, sandy silt and silt (channel infills).

3.2. Second site – Megaripples

The second site is located in the central part of the study area, on the channel that drained the bank of the Suchedniów water reservoir in 2017 (Fig. 2B). A detailed analysis of this material has allowed to distinguish three characteristic units, representing different sedimentary environments.

In the basal part of the succession, on well-sorted, fine-grained sands, lies a dark layer of silty sand with single gravels and small interbeds with fragments of wood detritus (branches). The thickness of this layer does not exceed 10 cm; it is characterised by about 30% of fine material (silt and clay), increased acidity and $CaCO_3$ content in comparison to other deposits. These deposits are covered with medium sand with rare gravels, forming another sedimentary unit. Fossil megaripples reach 56–94 cm in height and 230–320 cm in length. The average lee dip is about 25–40°, while stoss dip is about 29–30°. These megaripples consist of cross-stratified layers of sand and gravels (59% medium sand, 26% coarse sand, 14% fine sand and 1% gravel)

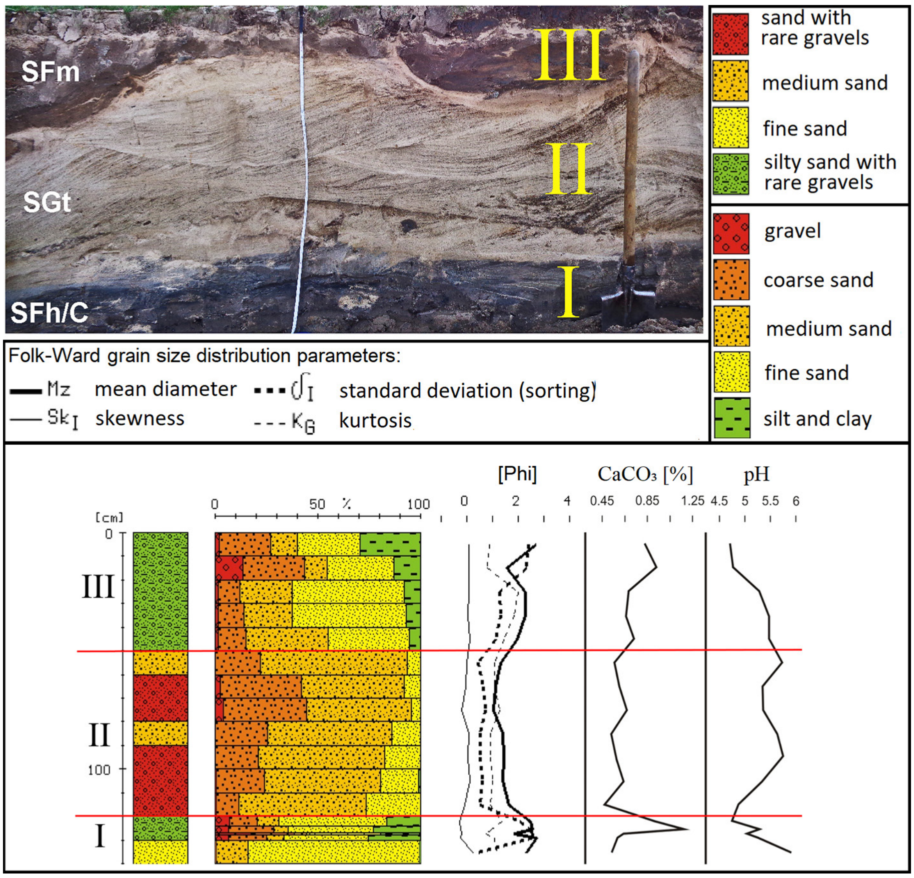

Fig. 9. Three intervals representing different sedimentary environments (second site); I – historical reservoir sediments, II – fossil megaripples, III – modern reservoir sediments. Lithofacies symbols: SFm – massive silty sand, SGt – gravelly sand with trough cross-stratification, SFh/C – horizontally stratified silty sand with organic detritus

(Fig. 9). The upper part of the succession comprises silty sand with rare gravels. The silty sand can be regarded as a typical lake sediment in a reservoir; this covers the bottom of almost the entire study area (Fig. 9). The orientation of forms visible on the surface of this site is WNW–ESE, intervals between them measuring about 1.5 m (Fig. 2A).

3.3. Third site – Dam

The third site is located in the northwestern part of the reservoir near the dam (Fig. 2B). In this place, the dam ruptured in 1974. After this catastrophic event, a dam weir was built here.

Three shallow wells were drilled in these lacustrine deposits: characteristic red sediments covered by a thin layer of silt and leaf fragments. The base of the succession shows angular rocky debris of the 0.5–3 cm size range. The thickness of the red interval is 30 cm; it is covered by 10 cm of silty sand with gravels. A detailed analysis of this material has documented a predominance of the sand fraction with gravels increasing to the top of the section. The silt-fraction admixture is small, around 5%; however, this material retains a very high plasticity. These properties are characteristic of regionally occurring fireproof clays, excavated for the production of ceramic products (Fig. 10) (Kalicki et al., 2018b, 2019).

3.4. Fourth site – Fishing spots

This site is located in the eastern part of the reservoir, being characterised by clearly visible longitudinal sandy bars on the basin bottom that are elongated perpendicularly to the reservoir bank (Fig. 4). These forms are more than 50 m long and about 20

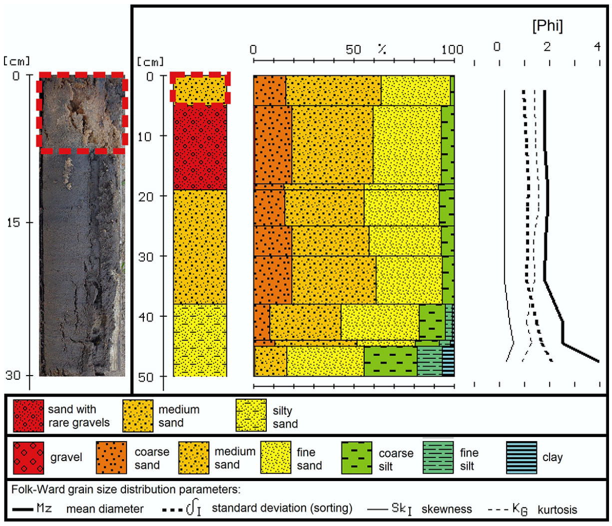

Fig. 11. Core of drill at fishing spots (fourth site), representing dark lacustrine sediments with an anthropogenically generated layer of yellow sand (red dashed lines)

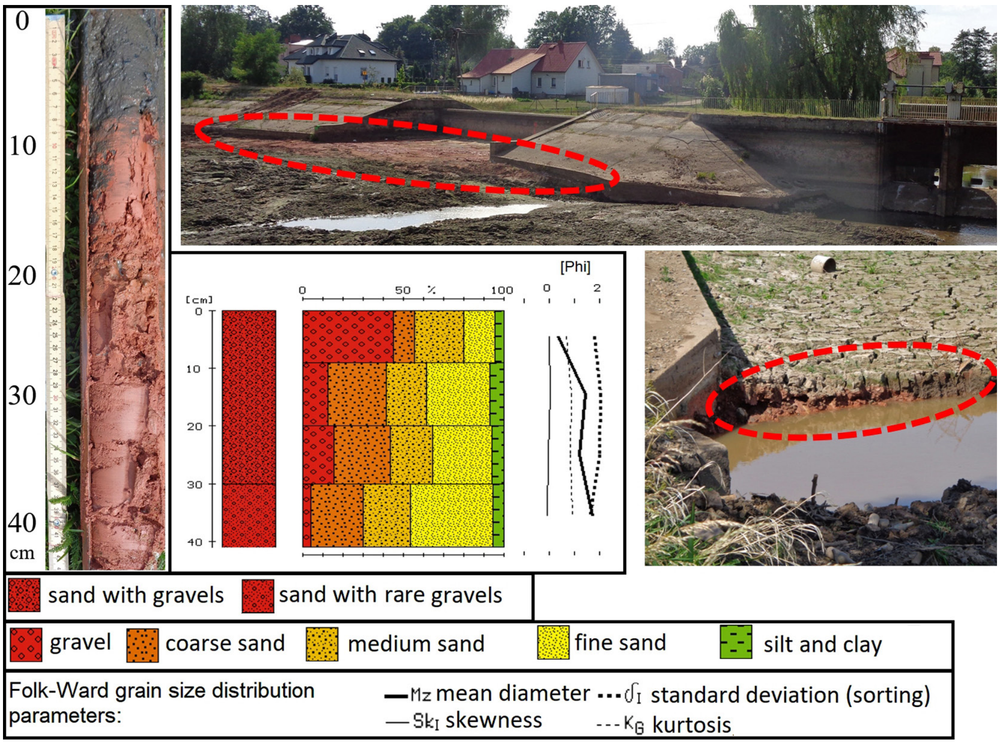

Fig. 10. Characteristic red sediments of fireproof clay (sand with rare gravels) covered by dark lacustrine sediments with concrete fragments (sand with gravels) accumulated near the dam (third site)

m wide. Drilling data and grain size analyses have documented a succession of dark silty sand covered by yellow medium sand (about 5 cm), moderately sorted (Fig. 11).

4. Discussion

On the basis of texture and structure of the deposits that accumulated in the estuary of the River Kamionka to the Suchedniów water reservoir can be regarded as fan delta sediments (McPherson et al., 1987; Nemec & Steel, 1988; Kim & Jerolmack, 2008; Rzętała et al., 2013; Zieliński, 2014; Gobo, 2014; Wang et al., 2015; Biesaga et al., 2018; Kalicki et al., 2018a, b). However, more precisely, they are transitional between subaqueous fan and fan delta. Its upper part was above the water (Fig. 5), which is a typical feature of fan deltas. In this emerged zone, numerous erosional channels formed. They document the subenvironment of a subaerial fan. On the other hand, it has no steeply inclined foresets due to the limited depth of the reservoir. The delta deposits may be divided into two units. The lower unit (sedimentary phases I–III in Figure 6) most likely form in the years 2005–2009, following regulation of the bed of the River Kamionka in the estuary section (after straightening of the channel that introduces water from the River Kamionka). The diversity of sediments in the upper unit of the delta (sedimentary phases IV–VII in Fig. 6) documents intensive accumulation of material transported by the river in the period 2009–2011 (S7 motorway construction and flood in 2010). Sand and silty sand, occasionally with an admixture of coarser grains (gravel), predominate in this reservoir part. Preserved in the median part of the Suchedniów water reservoir probably are lacustrine sediments of a previous historical pond from the early twentieth century, the existence of which is documented in historical and cartographic materials. Those sediments consist mainly of fine material (silt and clay) with two interbeds of detritus. The sandy megaripples (compare e.g., Boersma, 1969; Karcz, 1972; Julien & Klaassen, 1995; Carling et al., 2002; McCave & Geser, 2006) lying on them are most probably remnants of the sudden drainage of the reservoir following the dam break in 1974. A brief spell of heavy rainfall occurred on October 16, 1974, shortly after the construction works had finished. Data from the Skarżysko-Kamienna rain gauge have revealed that the year 1974 was characterised by increased rainfall, amounting to 149% (Żarnowiecki, 1996). High rainfall caused a significant flood, an increase of inflow to the reservoir and rupture of the dam. In the downstream reaches, the water level in the River Kamionka dramatically rose up to 4 metres above the mean stage and flooded some parts of Suchedniów (Piasta 2012; Kalicki et al., 2018a, b, 2019). The sands in the median part of the reservoir contain admixtures of coarser grains (0.5–5.0 cm gravels, slags and even modern ceramic fragments) that illustrate the high flow energy. These are overlain by a thick layer of modern lacustrine sediments (silty sand with rare gravels).

Grain size data of the sands of megaripples have been used for palaeohydraulical estimates. According to formulas by Allen (1965), Bogardi (1974), Saunderson & Jopling (1980) for mean critical flow velocity, it would appear that palaeoflow was 0.9–1.7 m/s. This calculation finds support in Cant (1978), who proved that the common configuration of the megaripple bed was formed by flows of 1.3 <v <1.5 m/s. Unfortunately, the palaeoflow velocity cannot be calculated from megaripple height. These formulas contain a palaeodepth parameter, which in this case is unknown. In our opinion, the origin of such large-scale bedforms can be regarded to have resulted from a violent hydrological event. Carling et al. (2002) reported that the formation of 2D megaripples of a height of 2 metres, i.e., analogous to those in the Suchedniów water reservoir, resulted from catastrophic discharge. The main genetic factor of megaripples in the Suchedniów water reservoir was the sudden drainage during a dam brake on October 16, 1974. The flood was documented by the Bzin hydrographic gauge station on the River Kamienna (co-ordinates 51°10′N, 20°86′E), by recording high water levels of 268 cm on October 16 and 396 cm on October 18 (230 cm being the alarm level). The discharge on October 16 was 5.29 m^3/s; the highest flow October 18 being 77.1 m^3/s (Rocznik hydrologiczny, 1974).

Sediments located at the site near the dam are characteristic of fireproof clay, locally excavated and processed in a nearby factory that produced ceramic products during the twentieth century (Stoch, 1964). It is likely that these sediments may have been transported by the river from embankments of the nearby S7 motorway and accumulated in the water reservoir (Górski et al., 2012). Shallow wells drilled across the reservoir area have documented a thin layer of red deposits (fireproof clay) in many places; these are very similar to material accumulated near the dam. The much larger thickness of these deposits at this site may indicate that the rebuilt part of the dam was strengthened by material of low permeability. The content of fine fraction in the red unit (less than 10%) is very similar to a fireproof clay deposit in the Baranów open-cast mine nearby (silt and clay content 4–15%) (Wyrwicki & Szmałek, 1986).

The coarsest grains in the lake sediments comprise sharp-edged clasts of aggregate, which rule out substantive fluvial transport. It may indicate that coarse material came from weathered dam elements (i.e., concrete and quartzite fragments).

Five sedimentary maps illustrate the spatial diversity of deposits at different depths (Fig. 12). A detailed analysis of the results indicates that coarse-grained material, mostly sand with rare gravels, accumulated in the central, northwestern and southeastern part of the reservoir. These are sediments that were formed near the dam, river estuary and anthropogenic beach (Fig. 2A). Gravelly sands in northwestern part of the reservoir represent a depositional event of a flash flood (i.e., during sudden drainage of the reservoir in 1974). In other zones, the coarse-grained material is anthropogenic in origin.

Medium and fine sand are regarded as natural fluvial supply. They derived from the bed of the River Kamionka or from glaciofluvial Pleistocene terraces along the valley studied. On the other hand, sand layers close to the reservoir banks were also put there by humans. In the western part of the reservoir some anthropogenically generated (fishermen) sandy bars exist (feeder method). This fishing method requires mixing bait with sand (to increase bait weight and looseness) that has resulted in the formation of sandy layers near fishing spots (Fig. 2A). Weak waves in this part of the reservoir, as well as the long timespan of regular fishing, has led to the preservation of these sands.

Fine deposits (silty sand, silt and clay) predominate in the eastern and northwestern part of the study area. These deposits are present on the entire reservoir bottom, but differ in thickness and depth of occurrence. They represent typical lacustrine deposits that have been found mainly in the northwestern part of the study area; they are probably related to the previous industrial pond from the first quarter of the twentieth century.

The modern reservoir sediments (recording the period 1974–2017) can be divided into anthropogenic and natural deposits. Sediments are the most diverse in the southeastern part, as a result of secular processes (delta). Anthropogenically generated sediments predominate in the western part (fishing spots, sandy bars, fireproof clay); however, deposits that accumulated mostly in a natural way (modern lacustrine sediments) predominate in the eastern part of the reservoir.

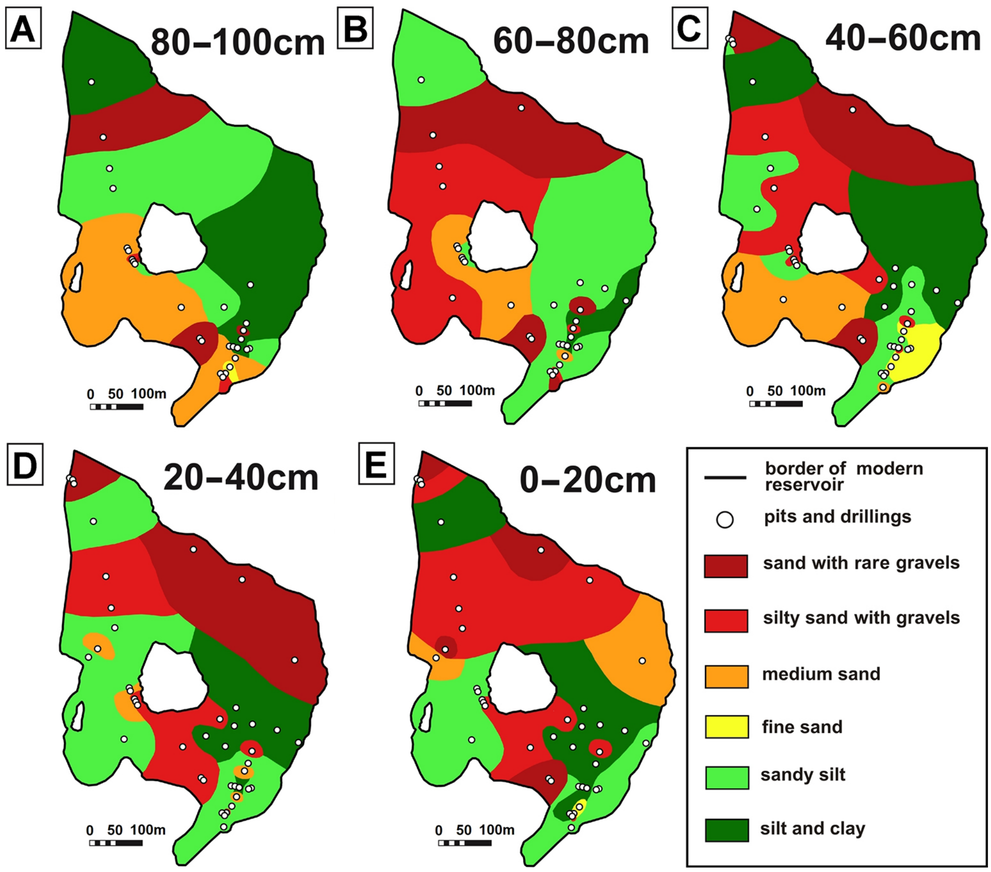

Fig. 12. Lithological maps of the Suchedniów water reservoir at successive depth intervals towards the surface

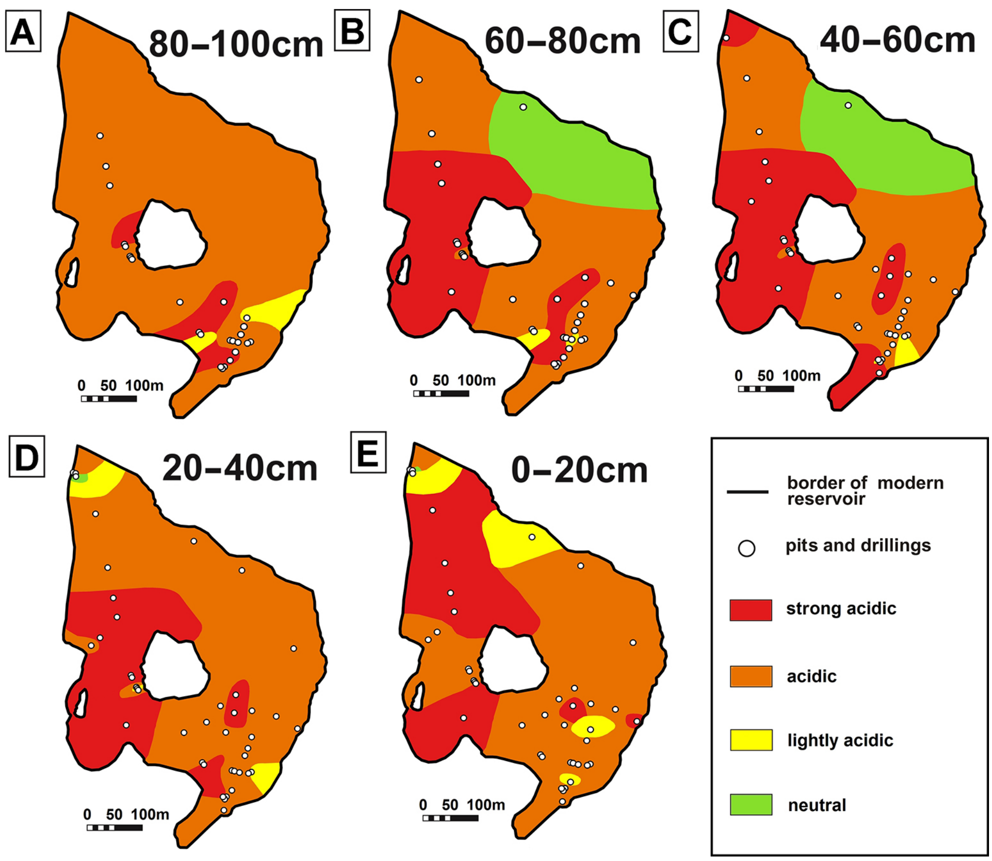

Fig. 13. Suchedniów water reservoir pH-scale maps at the successive depth intervals towards the surface

A predominance of very acid and acid pH is visible in reservoir sediments. A low acidic and neutral reaction occurs at depths of 0–20 and 20–40 cm in the northern part of the reservoir (near the dam) and at 40–60 and 60–80 cm in the northeastern part of the reservoir (Fig. 13). These data indicate that acidic reaction may be related to the washing away of calcium carbonate from lacustrine sediments. A higher content of calcium carbonate in the northern part of the reservoir could be related to the development of vegetation.

5. Conclusions

In the Suchedniów water reservoir, depositional forms and sediments are the result of both natural (normal and catastrophic) processes and anthropogenic activity. The time of their origin can be divided into the present-day period (fan delta, megaripple assemblage, fireproof clay layer) and a historical period (lacustrine sediments of the old industrial pond). Intensive silting of the reservoir represents periods of increased anthropogenic activity in the catchment area of the River Kamionka (e.g., motorway construction).

Large-scale sandy megaripples can be linked to the dam break in 1974 and sudden drainage of the reservoir. They occur in the constricted part of the reservoir where the flow was confined and therefore of high energy. Such bedforms in a lacustrine environment can be regarded as indicators of catastrophic drainage.

The bedforms created in the estuary of the River Kamionka to the reservoir can be classified as fan delta (presence of channel infills formed in the subaerial zone of the delta). However, it can be a form that is transitional to a subaqueous fan (due to the absence of steeply inclined foresets). Fan delta development began in 2005, after regulation of the estuary section of the river. Later, intensive construction works for the motorway in the years 2009–2011 accelerated accumulation by increased sediment supply from reworked embankments.

The lithological maps show a large spatial diversity of deposits in the study area. Textural and structural characteristics and thicknesses of sediments occurring in the Suchedniów water reservoir represent different sedimentary subenvironments. However, most of the sediments that accumulated in the reservoir are the result of human activity (Fig. 14). Human impact is recorded mainly in lithology

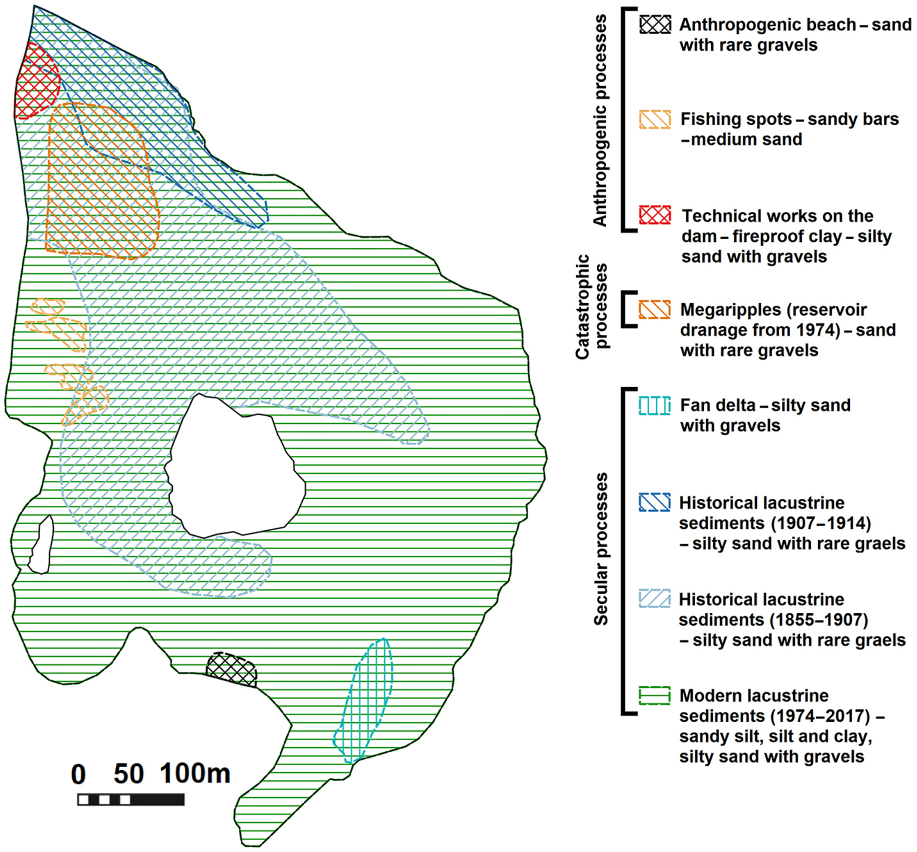

Fig. 14. Sedimentary model of the Suchedniów water reservoir, illustrating the most important changes in reservoir history and deposits

and sedimentation rates, whereas changes in geochemical features (pH) are seen only in a small portion of sediments.

The results obtained from the Suchedniów water reservoir may be used for the recognition of similar forms and sediments arising from both natural and anthropogenic factors in anthropogenic small-scale water retention systems (ASWRS), both in Poland and elsewhere.

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