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Water parameters and species composition of macrophytes in reclamation lakes in the area of a former sulphur borehole mine (SE Poland)

SUMMARY

Macrophytes and selected physical-chemical water properties were studied in 17 post-mining lakes of Jeziórko Sulphur Mine – one of the largest borehole sulphur mines in the world. Artificial lakes were constructed in subsidence depressions during the reclamation process of mining fields. They were characterized by high mineralization – conductivity ranged from 723 to 2295 μS/cm. The reaction was near neutral, or more frequently, slightly alkaline. Concentrations of phosphorus and organic matter were low. In the group of hydrophytes, *Ceratophyllum demersum*, *Myriophyllum spicatum*, *Najas marina*, *Utricularia vulgaris*, *Eleocharis acicularis*, *Potamogeton pectinatus*, *Potamogeton natans* and *Potamogeton pusillus* were frequently dominant. In several lakes, large macroscopic algae dominated – charophytes forming large, dense *Chara* meadows. In marsh communities, *Phragmites australis* was the most expansive. Reclamation process had a positive effect on diversity, some of the species found in the study area are regionally rare, including one species which is threatened in Poland (*Najas minor*). No alien species were recorded.

Keywords: post-mining lakes, sulphur mining, reclamation, aquatic vegetation, spontaneous succession, Jeziórko, SE Poland

STRESZCZENIE

Wybrane właściwości fizyko-chemiczne wody oraz skład gatunkowy makrofitów zostały przebadane w 17 zbiornikach na terenie dawnej kopalni „Jeziórko" – jednej z największych kopalni otworowych siarki na świecie. Sztuczne jeziora zostały zbudowane w nieckach osiadań terenu w procesie rekultywacji pól górniczych. Wody zbiorników charakteryzowały się wysoką mineralizacją, przewodnictwo elektryczne mieściło się w zakresie od 723 do 2295 µS/cm. Odczyn wód był neutralny lub częściej lekko zasadowy. Zawartości fosforu i materii organicznej były niskie. W grupie hydrofitów często dominowały *Ceratophyllum demersum*, *Myriophyllum spicatum*, *Najas marina*, *Utricularia vulgaris*, *Eleocharis acicularis*, *Potamogeton pectinatus*, *Potamogeton natans* i *Potamogeton pusillus*. W kilku jeziorach dominowały makroskopowe glony z rodzaju Chara, formując gęste łąki ramienicowe. W zbiorowiskach szuwarowych największą ekspansywność wykazywała trzcina pospolita *Phragmites australis*. Budowa zbiorników rekultywacyjnych miała pozytywny wpływ na bioróżnorodność, na terenie badań odnaleziono gatunki rzadkie regionalnie oraz jeden zagrożony w skali Polski (*Najas minor*). Nie stwierdzono obcych gatunków inwazyjnych.

Słowa kluczowe: zbiorniki pokopalniane, górnictwo siarki, rekultywacja, roślinność wodna, spontaniczna sukcesja, Jeziórko, SE Polska

INTRODUCTION

Mining is one of the human activities which heavily transform the landscape, often on a large scale. The environmental effects of mining depend on the type of extracted deposits, the mining techniques applied and the methods of reclamation used after the mine closure. Sulphur mining using the borehole method has a relatively low environmental impact but also causes soil and ground water pollution, generates terrain depressions, changes hydrographical conditions and damages large areas of vegetation cover (9, 21, 23).

Anthropogenic lakes and wetlands are common elements of the post-mining landscape, and they can be formed either in mining pits or subsidence depressions. During the reclamation process they can be liquidated or managed in various ways, and sometimes contribute to the development of valuable habitats and increasing local biodiversity (3, 17, 26, 27, 28, 37). Newly created post-mining lakes are usually oligo- to mesotrophic, and are frequently highly mineralized (7, 26). Water bodies in coal mine fields are also characterized by low pH values and heavy metal pollution. Deep open-cast lakes are meromictic due to a high concentration of mineral salt (7, 36, 39).

The development of biological life and ecosystem functioning in the conditions of post-exploitation lakes is undoubtedly an interesting research subject. A reasonably large amount of information about the vegetation and planktonic communities of sand pits, peat excavations and quarries are scattered throughout floristic, phytosociological and ecological studies (5, 7, 29, 30, 31, 34). The limnological research studies conducted in Central Europe in large mining fields of deposits such as coal, lignite or sulphur are less numerous and usually involve plankton (2) or invertebrates (11, 18), however, no literature is available concerning aquatic vegetation on land degraded by sulphur borehole mining.

Lake creation was applied as a rehabilitation method in the Tarnobrzeg Sulphur Region (SE Poland), where several dozen reservoirs of various sizes were created between 1996–2013. There are detailed studies of large open-cast mine lakes from this region, concerning hydrochemical conditions (33, 39), sediment composition (32), plankton (36, 40), benthos (6) and fishes (8). The surface water properties of various types of water body (backwaters, ditches, rivers and artificial reservoirs) in the Jeziórko Sulphur Mine were studied by Martyn and Jońca (22). Single observations of rare entomofauna in this area have also been published (19, 20).

The aim of the study was to describe the development of aquatic ecosystems in the early stages of spontaneous primary succession in the reclamation lakes of a closed sulphur borehole mine. The research included measurement of specific physical-chemical water parameters and the determination of the species composition and abundance of macrophytes. Moreover, the results of our research were used to evaluate reclamation effectiveness.

STUDY AREA

The Jeziórko mine is situated in the sub-mountain Carpathian basin in south-eastern Poland (N 50°33′, E 21°48′, altitude 150 m a.s.l.). It is part of a mining complex called the Tarnobrzeg Sulphur Region, where sulphur has been extracted since 1957 using both open-cast and borehole mining techniques. This complex is one of the biggest sulphur extraction areas in the world. In Jeziórko, sulphur deposits were excavated in 1967–2001 using the borehole method. This is the largest sulphur mine using this method in the world – 8,450 boreholes were drilled to exploit over 74 mln tons of sulphur (23). As the result of mining works, a large area has been polluted with sulphur compounds and acidulated. Subsidence depressions have developed in mining fields, flooded by extremely acidic water. The maximum level of depressions reached 6 m (9).

To regulate hydrographical conditions during reclamation treatment, a system of surface reservoirs and connecting ditches was built. In this way, the deepest parts of depressions were transformed into artificial lakes. The oldest reservoirs were built in 1996, the youngest in 2013. Finally the water was discharged into the reconstructed Żupawka stream. Reservoirs were built using indigenous materials. After lakes were formed, the acidification was neutralized with post-flotation sludge containing about 70% $CaCO_3$ (10) or commercial lime. Nowadays the lakes are used for public recreation purposes, mainly for fishing.

Tab. 1. Morphometric characteristics of post-mining lakes in Jeziórko

Lake number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Age [years]	3	13	14	11	12	11	13	13	12	19	19	5	6	2	7	4	–
Surface area [ha]	9.00	18.0	29.0	3.9	12.2	7.0	0.3	0.5	0.5	0.7	0.9	23.8	27.6	8.4	32.8	4.3	6.8
Depth [m]	2.3	2.0	2.0	2.0	2.0	2.0	1.5	1.5	2.0	1.3	1.9	2.3	2.5	2.3	2.5	2.5	0.8

Data source: The Mines and Processing Plants of Sulphur “Siarkopol” in Liquidation (2014)

MATERIALS AND METHODS

The study was carried out in 17 reservoirs located in the former Jeziórko Sulphur Mine. Most of them are artificial water bodies built in subsidence depressions. One study site (number 17) is an old clarifier. Data concerning the morphometry and age of reservoirs were obtained in 2014 from workers of *The Mines and Processing Plants of Sulphur “Siarkopol” in liquidation* in Tarnobrzeg (Tab. 1).

Multiparameter gauge HI 9828 was used to measure the basic physical-chemical properties of water: temperature, pH, dissolved oxygen, oxygen saturation, conductivity, TDS and salinity. Surveys were conducted in June 2014 at three points of the littoral zone for large reservoirs and two points for smaller ones. Additionally, selected chemical analyses were carried out in five lakes. The samples were taken in summer 2012 and analyzed by the Regional Environmental Protection Laboratory in Rzeszów. In this case the following methods were used: biological oxygen demand (BOD_5) – electrochemical method; chemical oxygen demand COD-Cr – titration;

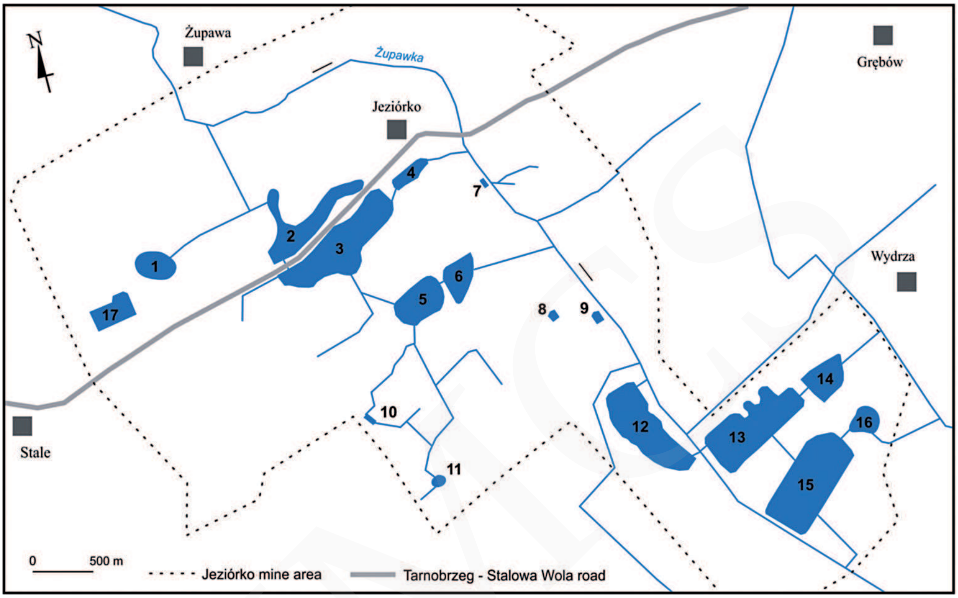

Fig. 1. System of water reservoirs and ditches constructed in subsidence depressions of mining fields in Jeziórko

ammonia nitrogen (N-NH_4), nitrate nitrogen (N-NO_2), dissolved phosphates and total phosphorus – spectrophotometry; nitrate nitrogen (N-NO_3) and sulphates (-SO_4) – ion chromatography (IC); total nitrogen – calculation method.

Macrophytes were surveyed in summer 2014. Plants were noted during wading in shallow water (to a depth of 0.7 m) along the banks of the lakes. Plants growing in deeper water away from the banks were sampled about every 250 m of the shoreline, using grapnel. Hydrophytes and typical helophytes (according to Zarzycki et al. (38)) were taken into account, other species were excluded. Species abundance was estimated with the use of the qualitative Tansley scale: 1 – sporadic, 2 – rare, 3 – occasional, 4 – frequent, 5 – abundant, 6 – co-dominant, 7 – dominant. Charophytes were determined using the Urbaniak and Gąbka guide (35).

RESULTS

Water properties

The results of analyses of the basic physical-chemical parameters for each single lake were very similar at particular measuring points, except for dissolved oxygen which differed considerably in some cases. In general, the waters of the investigated lakes were characterized by high mineralization. Conductivity ranged from 723 to 2295 µS/cm, which means a salinity of 0.35 – 1.18 in PSU. As expected, due to mining pollution, most of the lakes (all but three) are oligohaline. High mineralization is mostly the effect of a high concentration of sulphates (Tab. 3). The examined water samples were found to be near neutral or more frequently slightly alkaline, the mean pH value was 7.55 (range 6.88–8.33). Lakes were well oxygenized, with saturation at the bottom range from 22.6% to 92.5% (mean 64.4%). Chemical analysis showed that the concentrations of phosphorus as well as organic matter were low and quite similar in all of the five investigated lakes (Tab. 3). The concentration of nitrate nitrogen (N-NO_3) differed considerably, and reached relatively high values. As far as lake age is concerned, pH and amounts of dissolved oxygen are lower in older lakes.

Tab. 2. Physical-chemical properties of post-mining lakes in Jeziórko

Lake number	Measuring point	Temperature [°C]	pH	Dissolved oxygen [ppm]	Dissolved oxygen saturation [%]	Conductivity [µS/cm]	TDS [ppm]	Salinity [PSU]
1	1	21.7	7.84	5.72	68.0	2295	1147	1.18
	2	21.9	7.89	6.31	75.3	2292	1146	1.18
2	1	22.3	7.13	4.30	51.6	2064	1032	1.05
	2	22.0	6.95	4.04	48.2	2010	1005	1.03
	3	21.8	7.28	5.29	62.9	2077	1039	1.06
3	1	22.0	7.12	1.90	22.6	1910	955	0.97
	2	21.8	7.42	4.37	52.0	1872	936	0.95
	3	22.6	7.21	4.59	55.4	1894	947	0.96
4	1	22.3	7.37	5.80	68.5	1290	645	0.64
	2	22.5	7.40	5.69	67.5	1291	645	0.64
5	1	21.5	7.46	4.22	49.2	1720	860	0.87
	2	21.6	7.66	6.55	76.5	1758	879	0.89
6	1	22.0	7.59	6.26	73.6	1345	673	0.67
	2	21.9	7.66	6.26	73.4	1348	674	0.67
7	1	20.0	7.03	5.50	58.8	1302	652	0.65
	2	20.1	6.97	5.19	59.0	1300	650	0.65
8	1	19.8	7.37	4.79	53.5	1218	609	0.61
	2	18.8	7.30	4.01	44.0	1218	609	0.61
9	1	19.7	6.95	4.14	46.8	1302	621	0.66
	2	17.3	7.02	4.86	54.6	1319	659	0.66
10	1	19.5	6.93	4.23	47.2	2201	1101	1.13
	2	19.1	6.96	4.17	46.1	2202	1101	1.13
11	1	19.7	6.96	3.33	40.3	1927	963	0.98
	2	19.8	6.88	3.67	41.5	1925	963	0.98

12	1	21.8	8.07	7.09	82.9	798	399	0.39
	2	21.7	8.02	6.75	78.9	804	402	0.39
	3	21.9	7.93	6.28	73.5	806	403	0.40
13	1	21.7	8.03	6.94	81.1	1310	655	0.66
	2	21.1	8.08	6.79	78.5	1319	659	0.66
	3	21.6	8.08	7.25	84.5	1297	649	0.65
14	1	21.3	8.24	7.99	92.5	1181	591	0.59
	2	21.2	8.19	7.92	91.6	1179	590	0.59
15	1	21.1	8.33	7.81	90.0	1094	547	0.54
	2	20.1	8.24	7.22	81.3	1106	553	0.55
	3	19.5	7.88	6.61	73.6	1109	555	0.55
16	1	19.9	7.79	6.01	67.7	723	362	0.35
	2	20.2	7.78	6.42	72.6	724	362	0.35
17	1	19.1	7.84	5.58	62.7	751	375	0.37
	2	19.8	7.74	5.39	61.5	754	377	0.37

Tab. 3. Selected chemical parameters in five post-mining lakes in Jeziórko

Lake number	3	4	12	13	15
BOD_5 [mg/dm^3]	1.2 ± 1.0	2.6 ± 1.0	2.5 ± 1.0	2.2 ± 1.0	1.2 ± 1.0
COD-Cr [mg/dm^3]	44 ± 9	56 ± 11	69 ± 14	54 ± 11	64 ± 13
N-NH_4 [mg/dm^3]	< 0.05	0.068 ± 0.014	< 0.05	< 0.05	< 0.05
N-NO_3 [mg/dm^3]	1.45 ± 0.22	0.273 ± 0.041	< 0.1	3.23 ± 0.48	3.73 ± 0.56
N-NO_2 [mg/dm^3]	< 0.003	0.0032 ± 0.005	0.0050 ± 0.0008	< 0.003	< 0.003
N-total [mg/dm^3]	2,1 ± 0,3	1.3 ± 0.2	1.3 ± 0.2	4.0 ± 0.6	4.5 ± 0.8
-PO_4 [mg/dm^3]	< 0.05	< 0.05	< 0.05	0.104 ± 0.016	0.0515 ± 0.0077
P-total [mg/dm^3]	< 0.05	< 0.05	0.0624 ± 0.0094	0.0531 ± 0.0080	< 0.05

Macrophytes

In total, 42 aquatic plants were found in post-mining lakes (Tab. 4). Submergent plants were the most numerous among hydrophytes: *Ceratophyllum demersum*, *Myriophyllum spicatum*, *Najas marina*, *Utricularia vulgaris*, *Eleocharis* *acicularis*, *Potamogeton pectinatus* and *Potamogeton pusillus* were frequently dominant. From the group of aquatic plants with floating leaves, only *Potamogeton natans* and *Polygonum amphibium* fo. *natans* occurred frequently and developed in large patches, other species were sporadic. In several lakes charophytes were the predominant group, covering large parts of the lake bottom. Four species belonging to the *Chara* genus were found, the most numerous were *Chara vulgaris*. Pleustonic plants were poorly represented and covered only a small surface area.

Helophytes formed a more or less distinct belt of marsh communities. Common reed *Phragmites australis* was the most abundant species in the examined lakes. Cattails *Typha* spp. were also noted in most of the lakes, they occurred numerously, and sometimes co-dominated in phytocoenosis. Other helophytes occurred rather rarely and with small coverage.

As far as lake age is concerned, the number of species were higher in young lakes (2–7-year-old), mostly due to the increased number of submergent plants. Young lakes were preferred by such species as *Potamogeton pusillus*, *Potamogeton pectinatus*, *Chara contraria*, *Eleocharis acicularis*, *Myriophyllum spicatum*, *Najas marina*, *Najas minor* and *Alisma plantago-aquatica*. In the helophyte group, a proportion shift between dominants was observed, the share of *Phragmites australis* increased over time, while *Typha* spp. decreased.

Collating the data concerning species composition and salinity level, we found no pronounced relationship between them, but some general remarks can be made. In the most highly mineralized lakes, species from the genus *Chara* were commonly found, especially *Chara vulgaris* and *Ch*. *globularis*. The highest share of charophytes was in the two lakes with the highest salinity. From the group of vascular plants, salt resistance was shown by *Utricularia vulgaris*, *Typha latifolia*, *Typha angustifolia*, *Phragmites australis*, *Myriophyllum verticillatum*, *Myriophyllum spicatum*, *Lemna minor*, *Potamogeton natans*, *Potamogeton pectinatus* and *Schoenoplectus tabernaemontani*.

No clear species preferences were observed in the case of pH value, except for *Potamogeton pusillus* which occurred in alkaline lakes.

The number of studied species found in individual lakes ranged from 2 to 22. The largest diversity was observed in young lakes located in the southern part of the Jeziórko mine, characterized by higher pH and lower salinity levels (lakes 12, 13, 15, 16).

Tab. 4. Aquatic plants found in 17 reservoirs in the Jeziórko Sulphur Mine

Lake number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Alisma plantago-aquatica	3	2					1					4	4		2	3	
Bulboschoenus maritimus s.l.												3	1				
Callitriche sp.												1		2			
Ceratophyllum demersum	2		4		2	2		7	4			3	4		7	2	
Ceratophyllum submersum	1								7								
Chara contraria	5												4		2		
Chara globularis	5	2	4												2		
Chara virgata										5							
Chara vulgaris	7		2							5			5	2	5		
Eleocharis acicularis	3						4					3	4		5	5	
Eleocharis palustris	2					2		1	1			2	4		4	2	
Glyceria fluitans												2					
Glyceria maxima														3		1	
Hottonia palustris																1	
Lemna minor		2	3					4	4	2		1		3		1	
Myriophyllum spicatum	3		3	3	2							2	4	4	7	7	
Myriophyllum verticillatum		4	4		3									2			
Najas marina				6	7	6							7	4	4	7	1
Najas minor															4	4	
Nuphar lutea							5										
Nymphaea alba			1														
Phragmites australis	4	7	7	6	6	6	7	7	7	7	7	5	6	3	5	4	5
Polygonum amphibium			2	2	2				1			4	1	2			
Potamogeton crispus						2						3		1		2	7
Potamogeton lucens		2			2								3				
Potamogeton natans		5	5	5			3			7		5		2		3	

Potamogeton nodosus												2					
Potamogeton pectinatus	4		2	2		2						5	5		5		
Potamogeton perfoliatus																1	
Potamogeton pusillus s.s.	2											2	4	7	4	5	
Potamogeton trichoides			2			1						2					
Riccia fluitans			3														
Ricciocarpus natans			1														
Rorippa amphibia												1					
Rumex hydrolapathum								1	1				2				
Schoenoplectus tabernaemontani	3		2	2	2	1						1	2		3		
Sparganium emersum																3	
Sparganium erectum												2				2	
Typha angustifolia	3	4	7	3						1		4	4	3	4	3	4
Typha latifolia	3	4	3		2	2						5	3		2	3	4
Utricularia vulgaris		4	4		3						4			5	2	2	
Zannichellia palustris	2																
Number of species	16	10	18	8	10	9	5	5	7	6	2	22	18	14	17	20	5

DISCUSSION

The high concentration of dissolved mineral salts that is usually observed in post-mining lakes was also confirmed in the Jeziórko mine (Tab. 2). Similar conductivity to that found in anthropogenic reservoirs formed in lignite and coal mines (2, 18). Much higher salinity (up to 10 g/dm^3) was recorded near the bottom of a flooded opencast sulphur mine (39). Elevated mineralization is also observed in sand and gravel pits (27) and quarries (7).

The current neutral or slightly alkaline character of water in the Jeziórko mine is most probably the effect of liming new reservoirs, as well as the surrounding soils. Ten years earlier Martyn and Jońca (22) recorded a much lower pH in artificial reservoirs in Jeziórko, determining a mean value of 5.2. In deep excavation of an opencast mine in the same sulphur mining region, slightly alkaline water was generated by the limestone base (39). An extremely low pH (<3) was reached by water in lignite open-pits (2), however most anthropogenic water bodies were characterized by neutral or alkaline waters.

Many examples show that a small amount of organic matter and a low concentration of nutrients, especially phosphorus, is typical of newly created anthropogenic reservoirs (2, 7, 27). All these studies enable us to place such lakes along the trophy gradient in the group of oligo- or mesotrophic habitats. Similar states were observed in our study in the sulphur mine.

Anthropogenic reservoirs as a common element of the post-mining landscape play an important role for biodiversity in the reclamation process. During the colonization of new lakes, species composition is determined by site conditions, dispersal ability and inter-specific interactions – the meanings of these factors change over time, and as succession progresses. Dispersal that enables plants to reach a new site is an obvious and basic element in the initial phase of vegetation development. Landscape parameters and the availability of dispersal vectors determine the species emerging and the rate of succession. Aquatic plants can easily migrate, not only from near surroundings but from long distances (13). In Jeziórko we already found a high number of macrophytes in the 2–3 years after lake creation. Submergent plants dominated, as is characteristic of young water bodies. Charophytes occurred in high abundance in young lakes, they were also found in older ones, but in water with elevated salinity. This corresponds to the well known fact that during the succession process this group is pushed off into less suitable niches. In littoral marshes three common anemochorus species of helophytes were the most numerous (*Phragmites australis*, *Typha latifolia*, *Typha angustifolia*); these species are able to overgrow new sites fast, using vegetative propagation. Common reed is regarded as a very strong competitor that has caused the rapid decline of other aquatic species (4, 25); in Jeziórko it took the advantage in older lakes.

Comparing post-mining reservoirs in Jeziórko, which differ slightly in water parameters (especially mineralization), we found no clear reflection of these differences in species composition. But when we analyze diversity on regional scale we can reveal a dissimilarity of post-mining lakes in contrast to other aquatic habitats. Some of the species found in reclamation lakes in high abundance are rare or do not occur in other types of water bodies (old river beds, fishponds) outside the sulphur mine. According to ecological indicator values (38), among the vascular aquatic plants found in Jeziórko 62% are facultative halophytes. For comparison, in old river beds of small and medium rivers of the same region the share of halophytes was about 40% (14, 15), which suggests that elevated mineralization can affect vegetation structure.

Taking into account trophy state, it can be hypothesized that nutrient-poor water does not constrain the growing of plants typical of eutrophic habitats. The species observed in the examined lakes with a low concentration of mineral phosphorus are mostly eutrophic or generalist, only a few can be regarded as mesotrophic, e.g. *Eleocharis acicularis*, *Potamogeton trichoides*, *Bulboschoenus maritimus* and *Chara vulgaris* (1, 16, 38).

It must be emphasized that none of the examined water parameters reached extreme values, which would certainly have caused a decrease in species richness. For example, a low diversity of phytoplankton was observed in flooded lignite open-pits with a very low pH value (2).

Probably the major effect on species composition and, most of all on diversity, is limited competition, which is typical of the non-equilibrium state of newly created or disturbed lakes. Lack of vegetation or large areas of gaps in the vegetation in the littoral zone enable it to be settled by most of the plants which reach a lake. The habitat conditions of the new lake promote pioneer species, but at the same time do not limit the establishment of strong competitors. However, the importance of interspecific interaction increases over time, and species pools are reducing as a result of competitive exclusion. In 2–7-year-old lakes we noted on average 18 species, while in 11–19-year-old ones, only 8 species. Even if we eliminate small-size lakes from our calculations, the difference is still considerable (18 for young and 11 for older lakes). One of the best examples of the positive effect of excavation on diversity is the flora of a gravel pit flooded by shallow water in French Alps (27), where an extremely high species richness of submerged macrophytes, especially charophytes, was found. In natural landscape this effect is generated by free flowing rivers and their active floodplains (newly created and periodically disturbed river lakes or temporal pools), but river regulation has caused these habitats to be largely lost.

Some of the taxa (*Chara* spp., *Potamogeton pusillus*, *P. trichoides*, *Najas marina*, *Bulboschoenus maritimus*, *Schoenoplectus tabernaemontani*) seem to prefer new anthropogenic reservoirs, as they are frequently found in such habitats, while being generally rare. A good example is *Potamogeton pusillus* – a pioneer species colonizing newly created water bodies in the first years after excavation (5, 24, 25). *Najas marina* were found in subsidence depressions and gravel pits (18, 27). *Chara* spp. are quite frequent in peat excavations (29). Communities with *Potamogeton pusillus* and *Chara* spp. are also typical of oil sand mine reclamation wetlands in a boreal landscape (28). In natural ecosystems, species such as *Chara globularis*, *Potamogeton trichoides* and *Bulboschoenus maritimus* occur more frequently or exclusively in the young river lakes of active floodplains (14).

In short, the effect of limited competition on young anthropogenic aquatic ecosystem is essential to species composition and diversity; the chemical and physical factors of new anthropogenic reservoirs are less important as long as they do not reach extreme levels. Similar conclusions can be drawn from the literature review (26).

Based on the results of our study, an efficacy assessment of reclamation can be made in biological terms. In general, due to aquatic ecosystem loss, most of the native hydrophytes can be regarded as target species in reclamation. Some of the species found in the study area are regionally rare (*Najas minor*, *Najas marina*, *Potamogeton pusillus*, *Schoenoplectus tabernaemontani*, *Chara virgata*, *Chara contraria*) – from this group the first species is listed in the Polish Red Book (12). No alien species were recorded. Fast colonization by a large number of indigenous aquatic species and an increase in diversity on a local and regional scale are arguments for applied treatment. It can be concluded that creating artificial lakes which are then left for spontaneous succession is the right course of action in the reclamation of sulphur mining fields.

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REFERENCES

1. Amoros C., Bornette G., Henry Ch.P. 2000. A vegetation-based method for ecological diagnosis of riverine wetlands. Environ. Manage. 25 (2): 211–227.
2. Beulker C., Lessmann D., Nixdorf B. 2003. Aspects of phytoplankton succession and spatial distribution in an acidic mining lake (Plessa 117, Germany). Acta Oecol. 24: 25–31.
3. Chmura D., Molenda T. 2007. The anthropogenic mire communities of the Silesian Upland (S Poland): a case of selected exploitation hollows. Nat. Conserv. 64: 57–63.
4. Chun Y.-M., Choi Y. D. 2009. Expansion of *Phragmites australis* (Cav.) Trin. ex Steud. (Common Reed) into *Typha* spp. (Cattail) wetlands in northwestern Indiana, USA. J. Plant Biol. 52: 220–228.
5. Dubiel E., Nobis A., Nobis M. 2011. Flora roślin naczyniowych i zbiorowiska roślinne Zakrzówka (Kraków). Fragm. Flor. Geobot. Polonica 18 (1): 47–81.
6. Dumnicka E., Galas J. 2006. Distribution of benthic fauna in relation to environmental conditions in an inundated opencast sulphur mine (Piaseczno, reservoir, Southern Poland). Aquat. Ecol. 40: 203–210.
7. Galas J. 2003. Limnological study on a lake formed in a limestone quarry (Kraków, Poland). I. Water chemistry. Pol. J. Environ. Stud. 12 (3): 297–300.
8. Godlewska M., Jelonek M. 2006. Acoustical estimates of fish and zooplankton distribution in the Piaseczno reservoir, Southern Poland. Aquat. Ecol. 40: 211–219.
9. Gołda T., Haładus A., Kulma R. 2005. Geosozologiczne skutki likwidacji kopalń siarki w rejonie Tarnobrzega. Inż. Środ. 10(1): 59–73.
10. Gołda T. 2007 Wykorzystanie szlamów poflotacyjnych rudy siarkowej do rekultywacji terenów poeksploatacyjnych w górnictwie otworowym siarki. Inż. Ekol. 19: 79–88.

11. Kašovská K., Pierzchała Ł., Sierka E., Stalmachová B. 2014. Impact of the salinity gradient on the mollusc fauna in flooded mine subsidences (Karvina, Czech Republic). Arch. Environ. Prot. 40 (1): 87–99.
12. Kaźmierczakowa R., Zarzycki K., Mirek Z. (red). 2014. Polska czerwona księga roślin. Paprotniki i rośliny kwiatowe. Instytut Ochrony Przyrody PAN, Kraków.
13. Krahulec F., Lepš J. 1994. Establishment success of plant immigrants in a new water reservoir. Folia Geobot. Phytotax. 29: 3–14.
14. Krawczyk R. 2010. Species richness and vegetation structure in different morphogenetic types of river lakes in the San River valley. Annales Univ. M. Curie-Skłodowska, sec. C, 65 (1): 29–45.
15. Kubiak A.P., Krawczyk R. 2014. Diversity of macrophytes in riverine aquatic habitats: comparing river channel and its cut-offs. Annales Univ. M. Curie-Skłodowska, sec. C, 69 (1): 49–57.
16. Lacoul P., Freedman B. 2006. Environmental influences on aquatic plants in freshwater ecosystems. Environ. Rev. 14: 89–136.
17. Lewin I., Smolinski A. 2006. Rare and vulnerable species in the mollusc communities in the mining subsidence reservoirs of an industrial area (The Katowicka Upland, Upper Silesia, Southern Poland). Limnologica 36: 181–191.
18. Lewin I., Spyra A., Krodkiewska M., Strzelec M. 2015. The importance of the mining subsidence reservoirs located along the trans-regional highway in the conservation of the biodiversity of freshwater molluscs in industrial areas (Upper Silesia, Poland). Water Air Soil Pollut. 226: 189.
19. Lis Ł., Buczyński P. 2012. *Leucorrhinia pectoralis* (Charpentier, 1825) (Odonata: Libellulidae) w siedliskach wtórnych na terenie byłej kopalni siarki "Jeziórko" koło Tarnobrzega (Kotlina Sandomierska). Odonatrix 8 (1): 19–22.
20. Lis Ł. 2012. *Leucorrhinia albifrons* (Burmeister, 1839) (Odonata: Libellulidae) w siedlisku antropogenicznym na obszarze byłej kopalni siarki "Jeziórko" (Kotlina Sandomierska). Odonatrix 8 (2): 55–58.
21. Malinowski J., Perek M. 1994. Qualitative and quantitative variation of the groundwaters from the vicinity of Tarnobrzeg resulting from sulphur mining. Geol. Quarterly 38 (3): 593–602.
22. Martyn W., Jońca M. 2006. Wybrane właściwości chemiczne wód powierzchniowych w byłej kopalni siarki „Jeziórko" jako wskaźnik stanu środowiska po zakończeniu rekultywacji terenów górniczych. Acta Agrophys. 8 (2): 449–458.
23. Michno W., Dziedzic W., Czajkowski R. 2009. Przywracanie wartości użytkowych terenom górniczym na przykładzie KiZPS "SIARKOPOL". Materiały pokonferencyjne XIII Warsztatów Górniczych z cyklu „Zagrożenia naturalne w górnictwie", Bogatynia-Świeradów Zdrój, 17–19 czerwca 2009, pp. 197–211.
24. Nowak A., Nowak S., Czerniawska-Kusza I. 2007. Rare and threatened pondweed communities in anthropogenic water bodies of Opole Silesia (SW Poland). Acta Soc. Bot. Pol. 76 (2): 151–163.
25. Nowak A., Maślak M., Nobis M., Nowak S., Kojs P., Smieja A. 2015. Is the riparian habitat creation an effective measure of plant conservation within the urbanized area? Ecol. Eng. 83: 125–134.
26. Puchalski W. 1985. Post-exploitation water bodies – introduction to an ecological characteristics. Wiad. Ekol. 31 (1): 3–24.
27. Rey-Boissezon A., Auderset Joye D. 2012. A temporary gravel pit as a biodiversity hotspot for aquatic plants in the Alps. Arch. Sci. 65: 177–190.
28. Rooney R., Bayley S.E. 2011. Setting reclamation targets and evaluating progress: submersed aquatic vegetation in natural and post-oil sands mining wetlands in Alberta, Canada. Ecol. Eng. 37: 569–579.

29. Podbielkowski Z. 1960. Zarastanie dołów potorfowych. Monogr. Bot. 10: 1–144.
30. Podbielkowski Z. 1969. Roślinność glinianek woj. warszawskiego. Monogr. Bot. 30: 119–155.
31. Półtorak T. 1982. Zooplankton of post-gravel pit ponds and the zooplankton of Rzeszów dam reservoir covering their area now. Part I. Post-gravel pit ponds. Acta Univ. Nicolai Copernici, Nauki mat.-przyr. 52: 65–94.
32. Szarek-Gwiazda E., Galas J., Wróbel A., Ollik M. 2006. Surface sediment composition in an inundated opencast sulphur mine (Piaseczno reservoir, Southern Poland). Aquat. Ecol. 40: 155–164.
33. Szarek-Gwiazda E., Żurek R. 2006. Distribution of trace elements in meromictic pit lake. Water Air Soil Pollut. 174: 181–196.
34. Ślusarczyk A. 2003. Limnological study on a lake formed in a limestone quarry (Kraków, Poland). II. Zooplankton community. Pol. J. Environ. Stud. 12: 489–493.
35. Urbaniak J., Gąbka M. 2014. Polish Charophytes. An Illustrated Guide to Identification. Wydawnictwo Uniwersytetu Przyrodniczego we Wrocławiu, Wrocław.
36. Wilk-Woźniak E., Żurek R. 2006. Phytoplankton and its relationships with chemical parameters and zooplankton in the meromictic Piaseczno reservoir, Southern Poland. Aquat. Ecol. 40: 165–176.
37. Woch M.W., Trzcińska-Tacik H. 2015. High occurrence of rare inland halophytes on post-mining sites in western Ukraine. Nord. J. Bot. 33: 101–108.
38. Zarzycki K., Trzcińska-Tacik H., Różański W., Szeląg Z., Wołek J., Korzeniak U. 2002. Ecological indicator values of vascular plants of Poland. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.
39. Żurek R. 2006. Chemical properties of water in a flooded opencast sulphur mine. Aquat. Ecol. 40: 135–153.
40. Żurek R. 2006. Zooplankton of a flooded opencast sulphur mine. Aquat. Ecol. 40: 177–202.