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ORIGINAL ARTICLE

Conditions for development of anthropogenic meromictic reservoirs in the workings of crystalline rocks (based on the examples of the quarries of the Žulovská pahorkatina, NE Czech Republic)

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Abstract There are numerous anthropogenic water reservoirs in the vicinity of the Žulovská pahorkatina (northern Czech Republic). The vast majority of them have developed as a result of the flooding of the abandoned quarries of crystalline rocks (granites or granodiorites). The surface area of these water bodies is small and is <6000 m^2. These are, however, very deep reservoirs of up to 25 m. Permanent water stratification has been recorded in some of them; these are meromictic reservoirs. The development of the phenomenon of meromixis in the reservoirs that were studied was conditioned by the supply of organic matter from the catchment. The biochemical process of organic matter decomposition led to the release of ions, mainly NH_4^+. The accumulation of dissolved substances in the benthic zone initiated the meromixis phenomenon. Therefore, the water bodies that were tested can be classified as reservoirs of the biogenic type of meromixis. This article presents the stages of the evolution of a holomictic reservoir into a meromictic one. Three water bodies in which meromixis was recorded were selected for the study. The control object was an abandoned quarry reservoir with no meromixis.

Keywords Meromixis · Holomixis · Quarry reservoir · Organic matter · DOC · Plant colonisation

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Introduction

There are numerous anthropogenic water reservoirs in the vicinity of the Žulovská pahorkatina (Czech Republic) (Fig. 1). The vast majority of them emerged as a result of the flooding of quarries of crystalline rocks (granites or granodiorites). These water bodies are located in a temperate climate zone of the northern hemisphere. The mean annual air temperature in the study area is 8.6 °C. The warmest months are July and August, while the coldest are January and February (Table 1). The average annual air temperature in 2011 was 9.6 °C and about 1 °C higher than the average long-term temperature (1981–2010), which was 8.6 °C. In 2012, the average air temperature was 9.4 °C and higher compared to the long-term average by 0.8 °C (Table 1). Such differences are (naturally) typical of this climate zone. The average annual precipitation is 712 mm. On average, the highest precipitation is recorded in July, while the lowest in January (Table 1). The average wind speed is 2.3 m/s and thus can be described as weak winds. The lowest average wind speeds are observed in summer, while the highest in the period from December to May with a peak in April (Table 1).

A characteristic feature of the water bodies that are located in this climatic zone is the spring and autumn mixing of the entire mass of water down to the bottom (Hutchinson 1957). Water bodies of this type are referred to as holomictic. In some of the reservoirs that were studied, however, the phenomenon of meromixis was recorded. Meromixis in this climatic zone is a phenomenon that occurs in many places on Earth, while, at the same time, it is relatively rare (Hutchinson 1957; Boehrer and Schulze 2008; Hakala 2004; Hrdinka and Šobr 2010; Hrdinka et al. 2013).

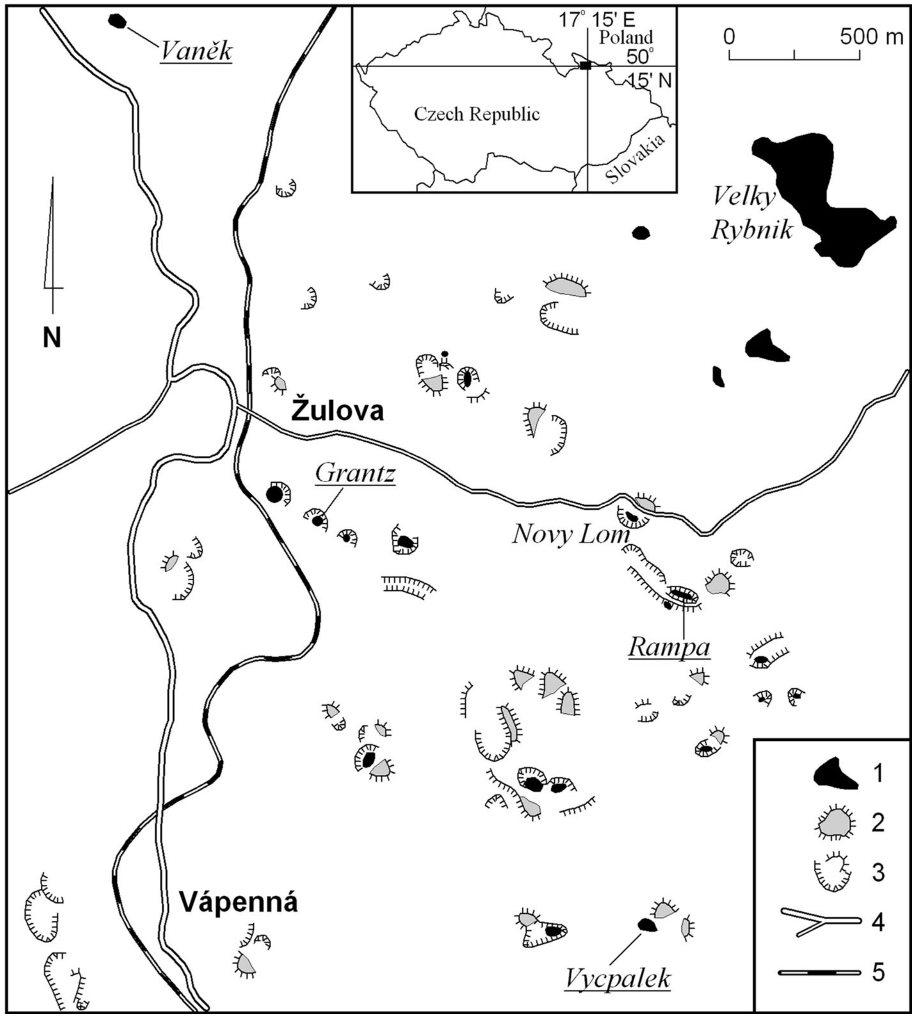


Fig. 1 Location of the research area: *1* anthropogenic water reservoirs, *2* gangue landfills, *3* edges of the post-exploitation workings (quarries), *4* roads, *5* railways

Table 1 Climatic characteristics of Żulovska pahorkatina: 1980–2010

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Average temperature of air (°C) (1980–2010)	−0.5	−0.3	3.3	8.2	13.3	16.0	18.1	17.8	13.7	9.7	3.6	0.6	8.6
Average temperature of air (°C) 2011 year	−0.2	−2.0	4.5	11.2	14.4	18.8	17.9	19.5	15.7	9.5	3.9	2.8	9.6
Average temperature of air (°C) 2012 year	0.1	−5.5	5.6	10.1	15.6	17.9	20.6	19.7	14.9	9.2	6.5	−1.0	9.4
Amount of fall (mm) (1980–2010)	25.3	31.8	45.2	50.5	76.1	102.8	114.2	82.3	69.7	38.6	42.2	33.6	712.3
Average speed of wind (m/s) (1980–2010)	2.4	2.3	2.4	2.6	2.4	2.1	2.1	2.1	2.4	2.2	2.3	2.3	2.3

In addition to natural lakes, meromixis has also been recorded in anthropogenic reservoirs. Most meromictic reservoirs occur in the post-exploitation workings of lignite (Dietz et al. 2012; Jędrczak 1992), sulphur (Wilk-Woźniak and Żurek 2005; Żurek 2002) and gypsum (Madonia et al. 2006). Meromixis can also be caused by the inflow of highly saline mine water (Galas 2003; Motyka and Postawa 2000; Molenda 2011, 2014) or the inflow of leachate from industrial waste landfills (Czop et al. 2011).

The purpose of this article is to present the conditions that can lead to the development of the phenomenon of meromixis in the post-exploitation workings of crystalline rocks.

Location of the research area

All of the reservoirs that were tested are located in the area of the Žulovská pahorkatina (Fig. 1). In terms of geological structures, the entire area is located within the unit of the Žulovsky Pluton (Žáček et al. 2004). The diversity of the geological structures of the area is relatively small. The

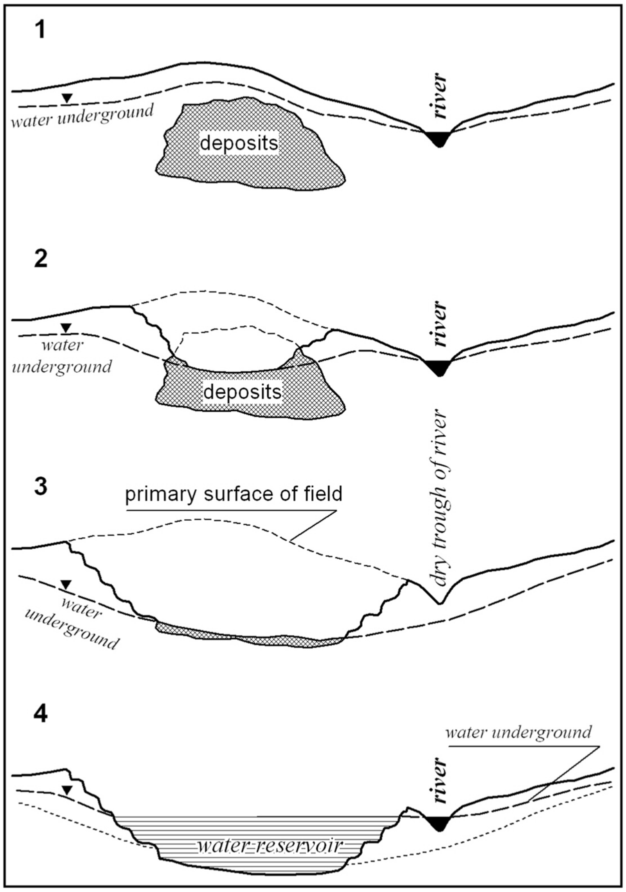


Fig. 2 Stages of excavation reservoir forming after Molenda (2011)

southern part is dominated by granitoids which correspond to the composition of granites or granodiorites (Stepancikova and Rowberry 2008). Occasionally, there are marbles, paragneisses and quartzites. There are loose sandy-gravel deposits in the northern part of the Žulovská pahorkatina.

The characteristic features of the relief of this area are the numerous granite quarries (Fig. 1). Their number is estimated to be about 50. They are usually small quarries of mixed slope and deep-seated types and less commonly of a deep-seated type. In addition to the quarries that are currently being used, there are numerous abandoned quarries where the operation has already been completed. Reclamation of these excavations has not been carried out since the completion of extraction. After the operations ceased, almost all of the workings were flooded with water. It was a natural, spontaneous process, not provoked by man. The stages of the creation of a quarry reservoir are shown in Fig. 2. As a result of such developments, the study area contains numerous anthropogenic water reservoirs (Fig. 1).

The water supply to the reservoirs is varied. Some of the water bodies are supplied only by the surface runoff and direct precipitation onto the surface of the basin. Other reservoirs are also supplied with groundwater. Although granite rocks are impermeable to water, they contain some aquifers that are correlated exclusively with cracks (Castany 1972). Groundwater outflows from the cracks in the quarry walls were observed in some of the quarries that were studied. In hydrological terms, endorheic basins dominate (no surface water outflow). There were only a few cases of outflow reservoirs. The outflow of water from the reservoirs occurs only during the periods of increased supply, i.e. during snowmelt in spring and during heavy rain in summer.

The following four reservoirs were selected for the detailed studies: Vycpálek (endorheic), Vanek (endorheic), Grantz (with outflow) and Rampa (endorheic) (Fig. 1). The reservoirs Vycpálek, Vanek and Grantz were flooded in the 1950–1960s. The time that has elapsed since the flooding is approximately 50 years. The reservoir Rampa was flooded in 1990, so its lifespan has been about 20 years. The basic morphometric parameters of the reservoirs that were studied are shown in Table 2. Bathymetric maps of the Vanek and Vycpálek reservoirs are also provided (Figs. 3, 4).

Research methods

Measurements of the basic physical and chemical properties of the water [temperature, pH, electrical conductivity (EC), saturation of water with oxygen and redox potential] were carried out directly in the field using an EDS 6600 multiparameter probe from the US company YSI. The probe was calibrated using standard solutions before each testing. The above-mentioned water parameters were determined in the reservoirs in water columns at 0.5 m. The profiles were located in the deepest parts of the reservoirs. Additionally, water transparency was determined using a Secchi disk (SD). The studies were carried out at specific times of the year—spring and autumn, i.e. during periods of complete water mixing. The details of the measurement dates are given in the description of figures and tables.

During the field research, water samples were collected for chemical analyses. Water samples for laboratory analyses were collected in polyethylene bottles of 0.5 L capacity. The samples that were collected represented the surface layer of water (0.5 m). The water surface layer was collected from a pontoon in the central part of the reservoir using a telescopic boom. The water samples from the bottom layers were collected using a bathometer by Eijkelkamp. Transportation of water samples to the laboratory was conducted at a temperature of +4 °C. The samples were filtered on 0.45 mm filter (Millipore) prior to the analyses. Laboratory analyses included the determination of the major cations and anions in the water: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+},

Table 2 Morphometric parameters of the excavation reservoirs

	Area (m^2)	Length (m)	Width (m)	Volume (m^3)	Depth max (m)	Coefficient Z_r
Vanek	5600	132	75	90,000	24	28
Vycpalek	2220	62	43	23,000	16	28
Grantz	1000	40	37	10,000	11	29.5
Rampa	2764	106	43	35,000	18	29

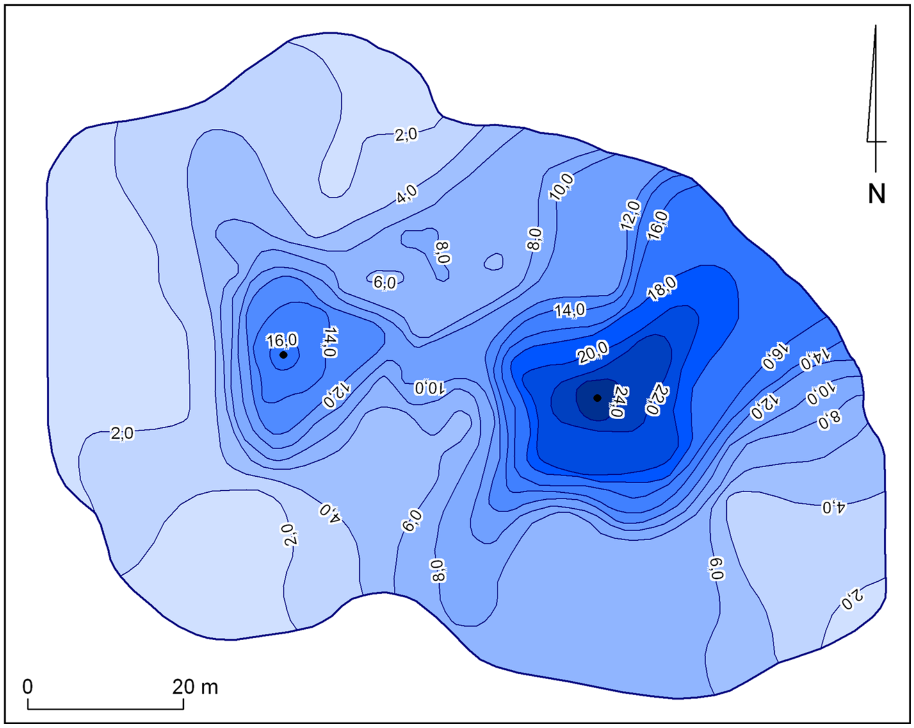


Fig. 3 Bathymetric plan of the reservoir Vanek

HCO_3^-, SO_4^{2-}, Cl^-, NO_3^- and PO_4^{2-}. The analyses were performed on a Metrohm 850 Professional IC ion chromatograph. Additionally, the concentrations of total organic carbon (TOC) and dissolved organic carbon (DOC) were also determined. The determination of the organic carbon was based on high-temperature combustion. The accuracy of this method is ±5 %.

The depth measurements were made from a pontoon using the sonar LOWRANCE HDS 5-Gen 2 with a built-in GPS receiver. On the basis of the measurement results, the bathymetric plans were plotted using a computer program Dr Depth. The basic characteristics and morphometric indicators of the reservoirs (length, width, volume, etc.) were calculated on the basis of the direct field measurements (laser rangefinder) and the plotted bathymetric plan. In the calculations used, the formulas were from the studies by Bajkiewicz-Grabowska and Magnuszewski (2002) as well as Choiński (2007).

To identify the type of bottom sediments (organic/mineral), their samples were collected by a Van Veen bucket by Eijkelkamp. Four samples were collected from each reservoir.

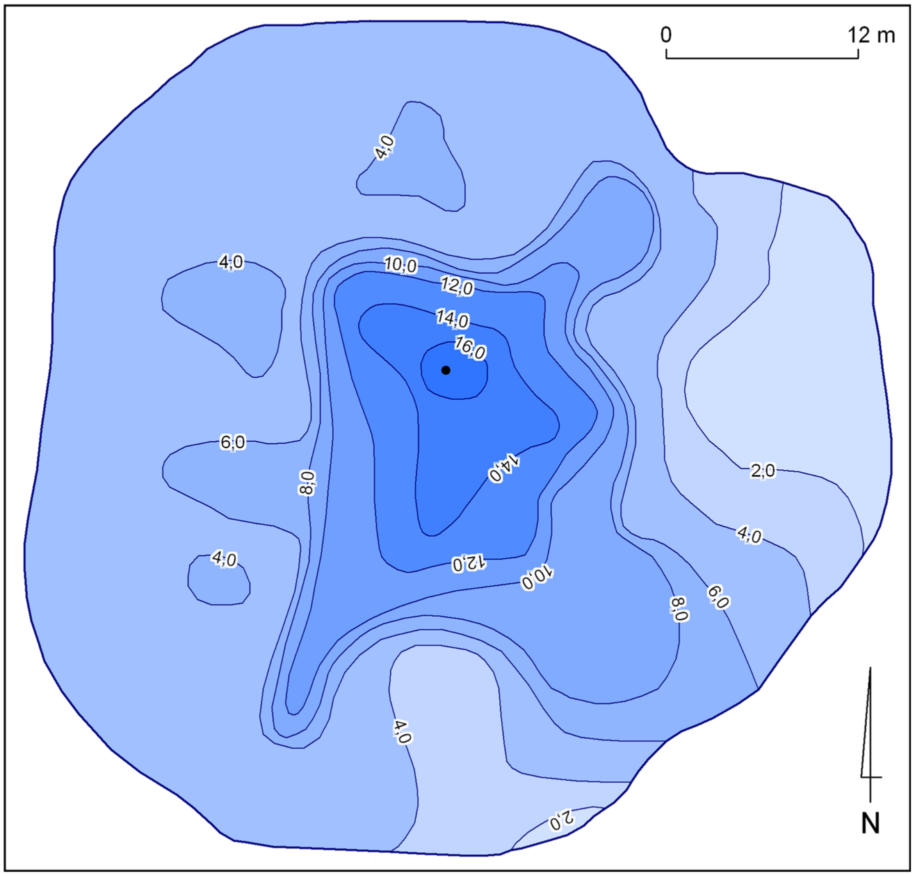
All of the statistical analyses in this study were performed using the R program (R Development Core Team 2009).

Results

The water in the flooded granite quarries is of the double-ion, calcium bicarbonate ($Ca–HCO_3^-$) hydrochemical type. The concentration of the major ions in the surface water layer of the tested reservoirs is shown in Table 3.

The electrical conductivity (EC) of the surface layer of the water is low. Its average value in the water bodies that were tested did not exceed 230 µs/cm. The lowest average conductivity value (146 µs/cm) was characteristic for the subsurface water of the Vycpálek reservoir. Significant differences in conductivity were observed in the vertical profiles of the reservoirs that were studied. A permanent increase of conductivity downwards was recorded in the Vanek, Grantz and Vycpálek reservoirs (Figs. 5, 6, 7). Higher conductivity values were observed in the benthic zone in both spring and autumn despite stable water

Fig. 4 Bathymetric plan of the reservoir Vycpalek



temperatures (Figs. 5, 6, 7). Thus, there is a permanent stratification that is characteristic of meromictic lakes.

In the case of the Vanek reservoir, significant differences in conductivity were observed between the surface water layer and the bottom layer in both spring and autumn (Fig. 5). The difference was 420 µs/cm in spring. An almost identical situation was observed in autumn. A very big difference was also recorded in the Grantz reservoir: 560 µs/cm (Fig. 6). A smaller difference (130 µs/cm) was found in the Vycpálek reservoir (Fig. 7). In the case of the Rampa reservoir, there was a complete mixing of the water down to the bottom and an alignment of electrolytic conductivity in both spring and autumn (Fig. 8).

A lack of full mixing in the Vycpálek, Vanek and Grantz reservoirs was also confirmed by the analysis of the oxygen and redox potential profiles (Figs. 9, 10, 11). In all of the reservoirs in which there were significant differences in the vertical distribution of conductivity in spring and autumn, the same differences were found for oxygenation and redox conditions. There were anaerobic conditions in the monimolimnion waters of the meromictic reservoirs (Figs. 9, 10, 11). It should be noted that the oxygen saturation of the mixolimnion water was very small and between 30 and 85 %. The monimolimnion water also had a negative redox value (Figs. 9, 10, 11).

The course of the thermal profiles in the Rampa reservoir is typical for spring and autumn (Fig. 8). The water temperature throughout the vertical profile was aligned and amounted to ≈4 °C. An increase in temperature was observed at the bottom to about 5.5 °C in the meromictic reservoirs (Figs. 5, 6, 7). The presence of water of such high temperature under the layer of water 40 °C, which theoretically has the highest density, should not occur. However, such a situation is possible because the density differences that are subject to temperature changes are smaller than those that result from mineralisation.

A large concentration of dissolved organic carbon (DOC) (Table 3) was recorded in the meromictic reservoirs (Table 2). The significant amount of dissolved humic substances influenced the colour of water, which is yellow-brown. Transparency is also very low in the meromictic reservoirs. The lowest average water transparency was found in the Grantz reservoir (SD 0.9 m). In the holomictic Rampa reservoir the water transparency was higher (SD 3.4 m).

Discussion

The electrical conductivity of the surface layer of the water in the reservoirs that were studied is small in relation to

Table 3 Physico-chemical properties of surface water (Mean ± standard deviation, $n = 8$)

	EC (us/cm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	HCO_3^{-} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)	NO_3^{-} (mg/L)	PO_4^{3-} (mg/L)	TOC (mg/L)	DOC (mg/L)	SD (m)
Vanek	230 ± 24	33.6 ± 3.5	5.7 ± 1.9	4.8 ± 0.9	4.6 ± 0.6	122 ± 16.9	7.2 ± 2.3	10.4 ± 3.9	2.8 ± 2.2	0	8.9 ± 1.4	7.9 ± 0.8	1.2 ± 0.4
Vycpalek	146 ± 25	21.4 ± 3.4	2.5 ± 0.1	3.5 ± 0.1	4.1 ± 1.9	82.7 ± 6.6	2.1 ± 0.3	2.5 ± 0.7	0.2 ± 0.2	0	7.7 ± 1.0	6.7 ± 0.6	1.7 ± 0.4
Grantz	210 ± 22	32.6 ± 3.1	4.0 ± 0.9	6.3 ± 0.9	2.7 ± 0.1	107 ± 15	5.8 ± 0.7	9.4 ± 0.1	0.1 ± 0.1	0	11.3 ± 2.2	6.8 ± 0.6	0.9 ± 0.3
Rampa	157 ± 10	18.4 ± 1.1	1.7 ± 0.4	1.7 ± 0.4	2.0 ± 0.3	65.4 ± 2.7	5.6 ± 1.4	7.7 ± 2.2	0.4 ± 0.3	0	3.1 ± 0.5	2.6 ± 0.4	3.4 ± 0.4

Sampling: January, April, August and November 2011, January, April, August and November 2012

other anthropogenic water bodies that have been described in the literature (Rzętała and Jaguś 2011; Wilk-Woźniak and Żurek 2005). A low electrolytic conductivity of water is conditioned by the lithological-mineral factor of the rock medium. The contact of the water with the crystalline rocks has no great effect on the increase of water mineralisation. They are poorly soluble rocks and thus affect the increase of the water mineralisation insignificantly (Macioszczyk 1987). Similarly, low conductivity values were also recorded by Hrdinka (2007) and Molenda (2011) when examining other reservoirs in the working of crystalline rocks.

Consistent differences in the water conductivity of the surface and near-bottom layers, which were identified both in spring and autumn, prove the meromictic character of the reservoirs. The reservoirs are located in a temperate climate zone, in which full mixing occurs both in spring and autumn, i.e. the reservoir water mixes from the surface down to the bottom (Hutchinson 1957). A consequence of the mixing is the unification (homogeneity) of the physico-chemical properties of the water in the vertical column of the reservoir (Choiński 2007). There were no such conditions in the water bodies that were studied. Similarly, a permanent distribution of conductivity has also been reported in other meromictic reservoirs of an anthropogenic origin (Dietz et al. 2012; Żurek 2002; Chmura et al. 2013) as well as in natural lakes (Hongve 1980; Kazanci et al. 2008). Moreover, anaerobic conditions and negative values of the redox potential in the bottom water layer of the water confirm the meromictic nature of the water bodies that were studied.

The development of the meromixis phenomenon in the water bodies that were studied was gradual. In the initial period, just after the flooding, the reservoirs were holomictic. The mixing of the entire mass of water down to the bottom took place during both the spring and autumn circulation. This is confirmed by the example of the 'young' Rampa reservoir, for which a homogeneous distribution of electric conductivity, oxygen saturation and redox potential were recorded during the circulation (Figs. 8, 12). Such conditions clearly indicate the full mixing of waters (Hakala 2004). The evolution of a holomictic reservoir into a meromictic type proceeded gradually over the time that had passed since the flooding of the quarry. A key role in this process was played by vegetation.

Over time, gradual plant colonisation led to the development of a vegetation cover within the former quarry (Fig. 13). The process of the plant colonisation of the quarry workings has been described in numerous papers (Błońska et al. 2013; Chmura et al. 2013; Chmura and Molenda 2007). Growing vegetation is a major source of

Fig. 5 Vertical distribution of conductivity and water temperature in the reservoir Vanek (*a* Nov. 2011, *b* April 2012, *c* Dec 2014)

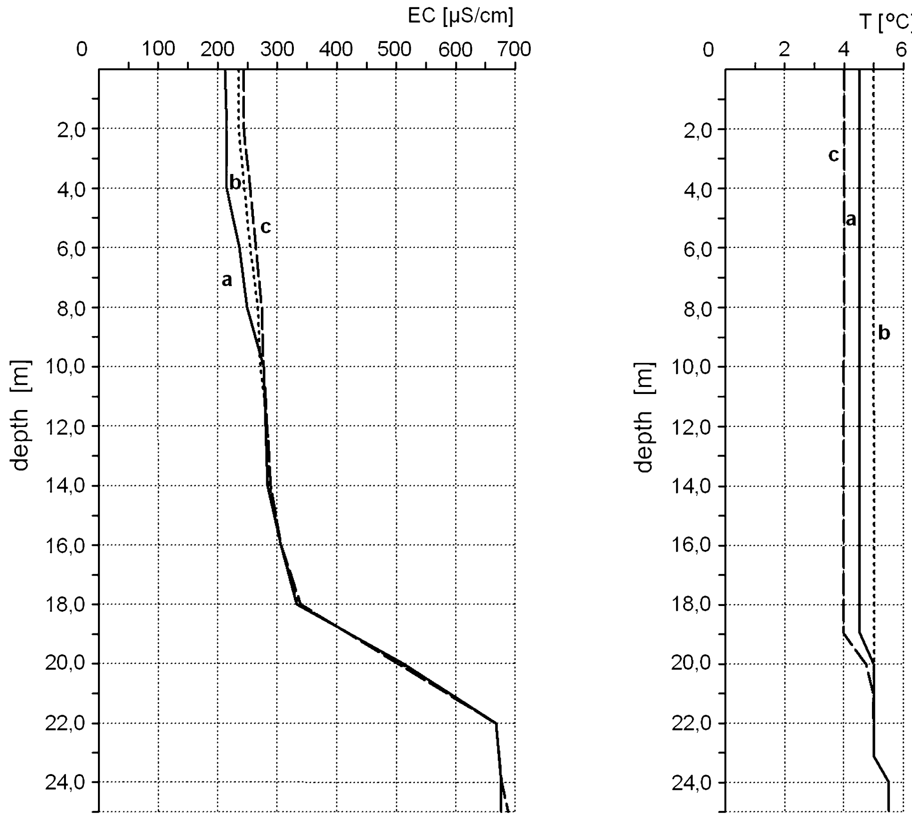
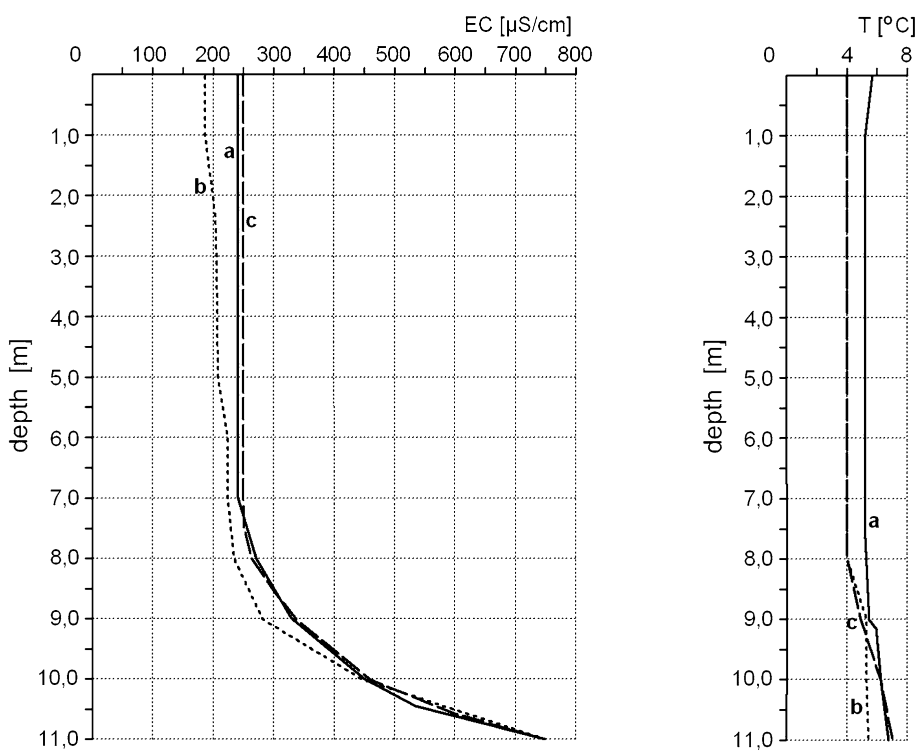


Fig. 6 Vertical distribution of conductivity and water temperature in the reservoir Grantz (*a* Nov. 2011, *b* April 2012, *c* Dec 2014)



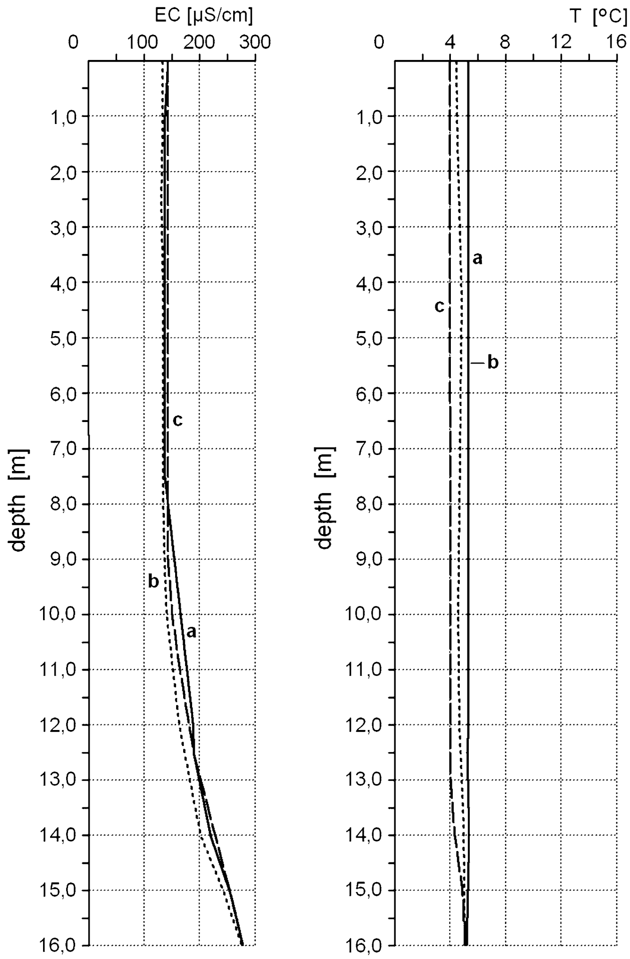


Fig. 7 Vertical distribution of conductivity and water temperature in the reservoir Vycpalek (*a* Nov. 2011, *b* April 2012, *c* Dec 2014)

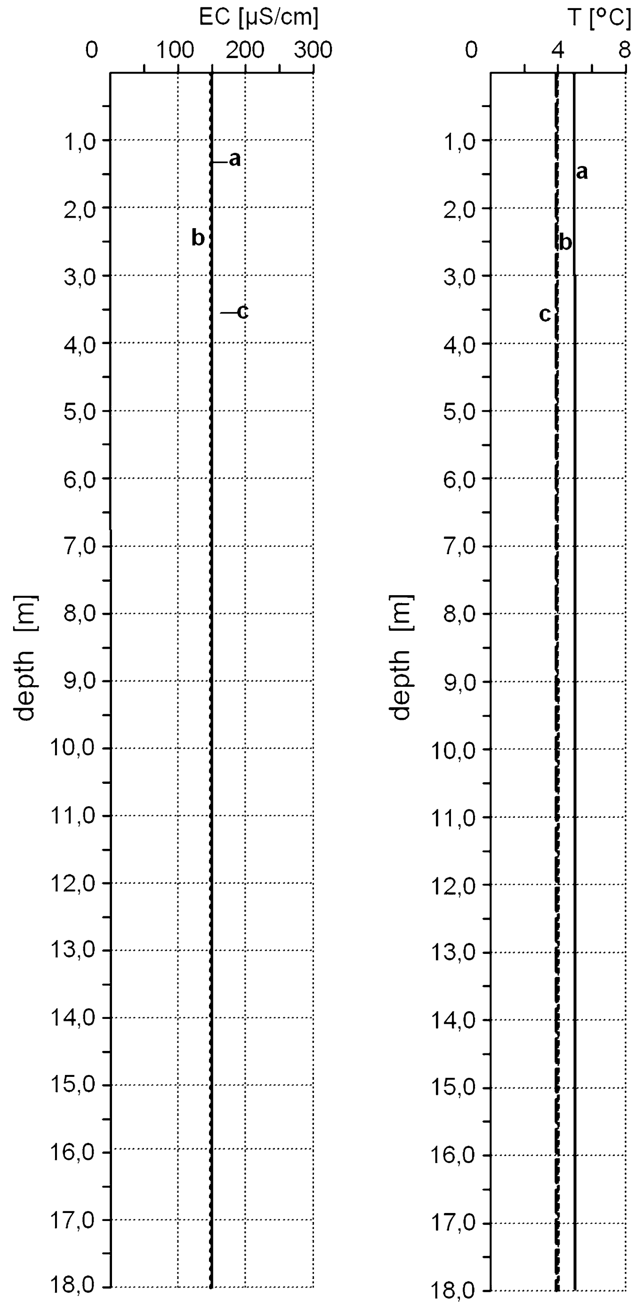


Fig. 8 Vertical distribution of conductivity and water temperature in the reservoir Rampa (*a* Nov. 2011, *b* April 2012, *c* Dec 2014)

autochthonous detritus. It consists of plant tissues—especially tree leaves and branches that fell onto the surface of the reservoir. In the case of the described quarries, the main tree species that colonises the excavation is birch (*Betula pendula Roth*) (Fig. 14). It is a typical pioneer species, which first enters abandoned excavations. Two other pioneer species, pine (*Pinus sylvestris* L.) and aspen (*Populus tremula* L.), have a smaller participation. In the waterlogged places, in the shoreline zone, there is also black alder (*Alnus glutinosa* Gaertn.) (Fig. 15). This species has also colonised other excavations with waterlogged floor.

The bottom of the meromictic reservoirs is completely covered with a layer of leaves. These were always leaves collected during the sampling with the van Veen bucket, and never mineral deposits (Fig. 16). These were mainly birch and black alder leaves of varying degrees of decomposition. The supply of large quantities of organic matter in small-capacity reservoirs causes a rapid increase in the amount of total organic carbon (TOC). Another source of organic matter is autochthonous detritus, such as *Lemna minor*, which occur in the water bodies that were studied. The analysis of Table 3 shows that the dissolved organic carbon concentration (DOC) in the water of the meromictic reservoirs is greater than that recorded in the Rampa reservoir. It is also greater than those found in most lakes (5–7 mg/L) (Górniak 2001; Dunalska et al. 2003, 2006).

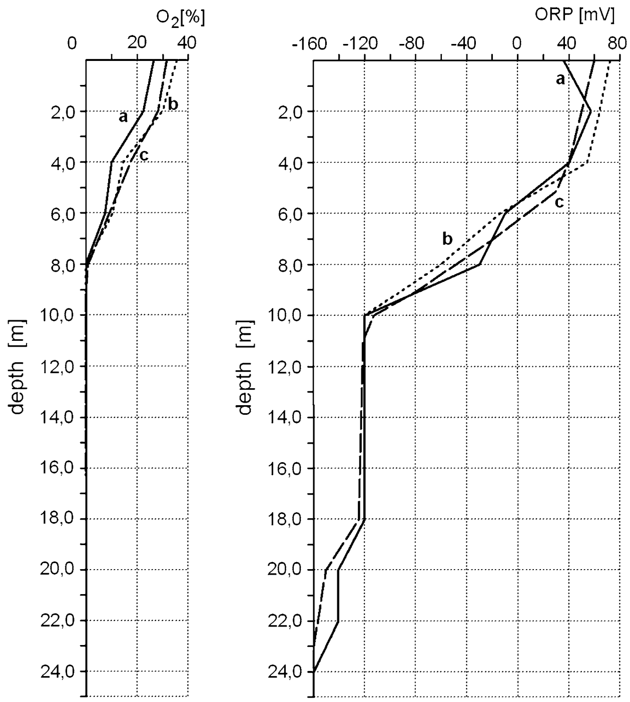


Fig. 9 Vertical distribution of water saturation with oxygen and redox potential in the reservoir Vanek (*a* Nov. 2011, *b* April 2012, *c* Dec 2014)

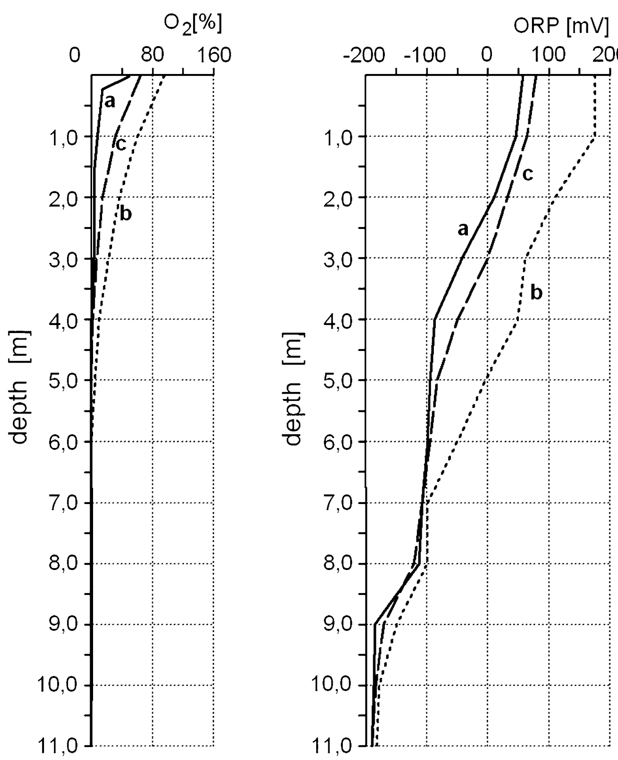


Fig. 10 Vertical distribution of water saturation with oxygen and redox potential in the reservoir Grantz (*a* Nov. 2011, *b* April 2012, *c* Dec 2014)

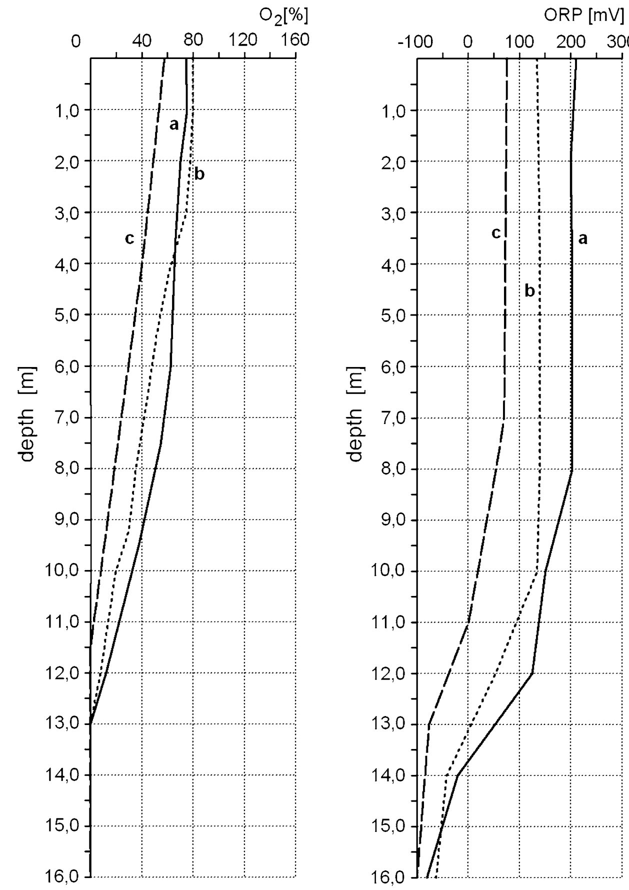


Fig. 11 Vertical distribution of water saturation with oxygen and redox potential in the reservoir Vycpalek (*a* Nov. 2011, *b* April 2012, *c* Dec 2014)

The water of the meromictic reservoirs that were tested has a yellow-brown colour. This is due to the considerable amount of soluble humic substances. As the research by Górniak (1996) indicates, their source may be the process of organic matter humification. A significant amount of dissolved humic substances affects the transparency of the water, which is reflected in the poor visibility of the Secchi disk (Table 3). The minimum value of the Secchi disk visibility in the Grantz reservoir is only 0.6 m. An even lower value of the Secchi disk visibility (<0.5 m) was recorded by Molenda (2011) in other meromictic reservoirs of this type. In the Rampa reservoir, which has a low concentration of dissolved organic carbon (DOC), the average visibility of the Secchi disc is 3.4 m.

Autochthonous and allochthonous organic matter, which falls to the bottom in the autumn, is subjected to the biochemical processes of decomposition which lead to the release of ions, including ammonium ions. This type of mineralisation is called ammonification (van Loon and Duffy 2005). In all meromictic reservoirs, there is a statistically significant higher concentration of NH_4^+ ions in

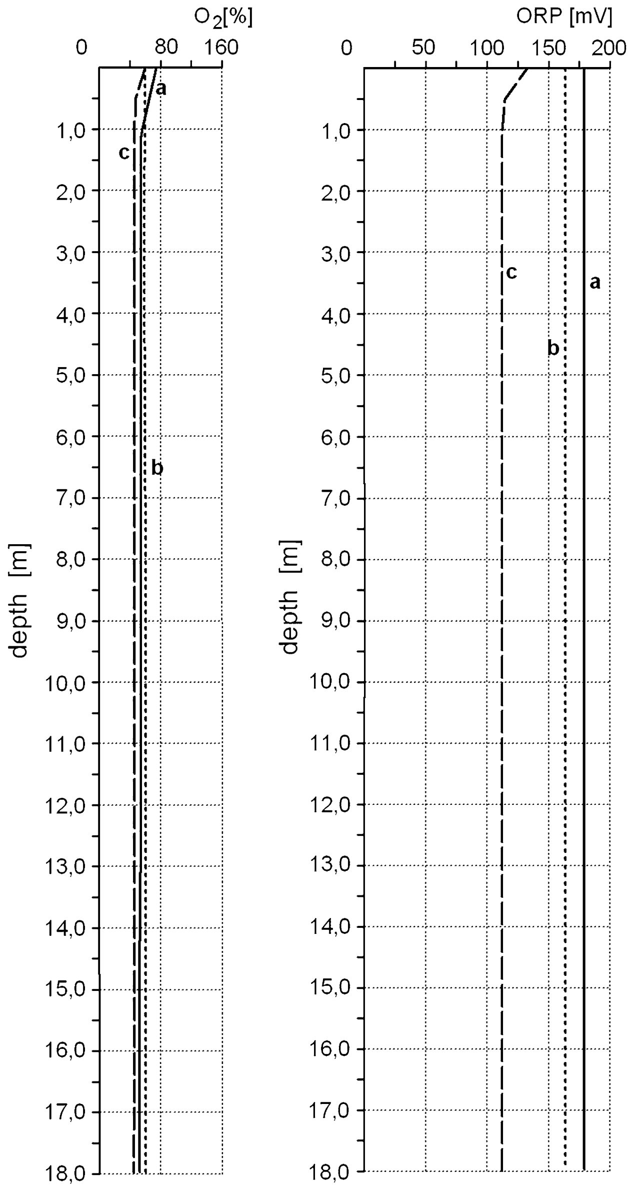


Fig. 12 Vertical distribution of water saturation with oxygen and redox potential in the reservoir Rampa (*a* Nov. 2011, *b* April 2012, *c* Dec 2014)

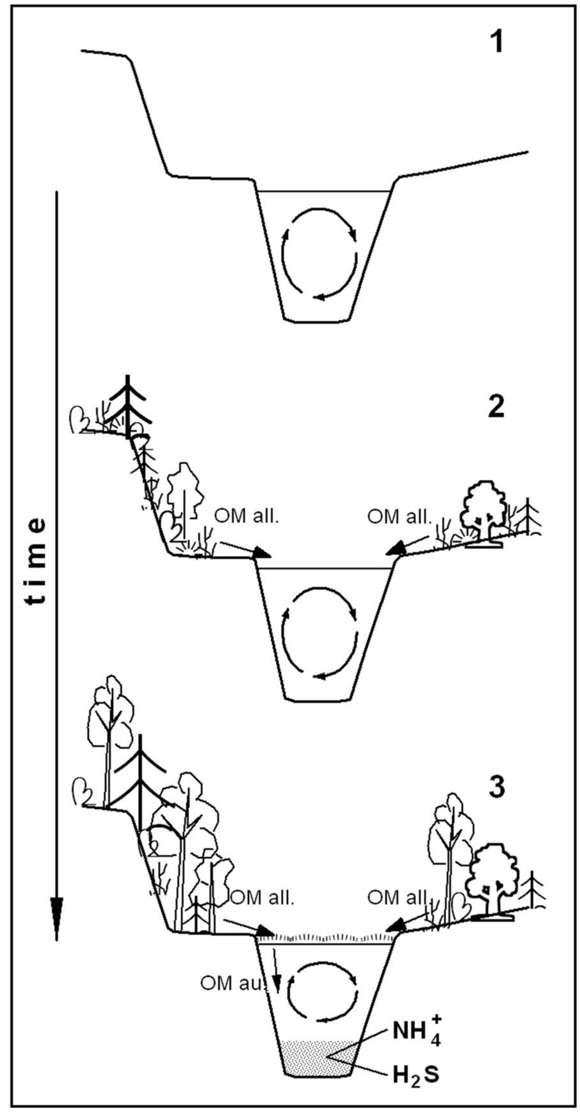


Fig. 13 Changes in mixing processes in quarry reservoirs: *1* initial stage of the existence of the reservoir (holomictic reservoir), *2* initial stage of plant colonisation of the working (holomictic reservoir), *3* advanced process of plant succession (meromictic reservoir). *OM All.* allochthonous organic matter, *OM Au.* autochthonous organic matter

the bottom water relative to the subsurface water (Fig. 17). Such differences are not found in the case of the reservoir Rampa. The accumulation of these substances and, as a result, an increase in the density of the water initiate the meromixis phenomenon (Fig. 13). Therefore, the reservoirs that were studied are characterised by a biogenic meromixis.

The existence of meromictic conditions would not have been possible if not for the unique morphometry of the basins of the reservoirs. An indicator that shows the relationship between the depth and the surface well is relative depth (Z_r). The higher the Z_r ratio, the greater is the likelihood that meromictic conditions will develop in a given reservoir. According to Hongve (2002), favourable conditions for the occurrence of the meromictic conditions are when $Z_r > 8$ %. In the water bodies that were tested, the Z_r ratio has a very high value of 28–29 % (Table 2). In other anthropogenic meromictic reservoirs, e.g. those in Poland, this ratio ranges from 20 to 30 % (Jędrczak 1992). The surface area of the water bodies is also an important factor. Salonen et al. (1984) indicate that the surface area of the water bodies that are predisposed to the occurrence of meromixis is <30,000 m^2. This criterion was also met by all of the reservoirs that were analysed. In addition, the reservoirs are located in working of mixed slope and deep-seated types of quarries. This further reduces the impact of

Fig. 14 Initial colonisation in the quarry Rampa—the dominance of birch (*Betula pendula* Roth)

Fig. 15 Advanced plant succession in the quarry Grantz—domination of black alder (*Alnus glutinosa* Gaertn.)

wind on the water surface. In some of the quarries, the wall height from the water table to the edge of the pit is >20 m.

Conclusions

Once quarry exploitation ceased, the test pits were flooded with water. It was a natural, spontaneous process, not supported by man. In the absence of reclamation, the quarry slopes have also been the subject of colonisation by vegetation. In the initial period of the operation, the reservoirs in the working of crystalline rocks are holomictic. This is supported by the example of the 'young' reservoir Rampa. The transformation of a holomictic reservoir into a meromictic type is gradual and connected with the development of vegetation and delivery of the organic matter

Fig. 16 Bottom organic sediments (leaves of varying decomposition) obtained from the reservoir Vycpálek

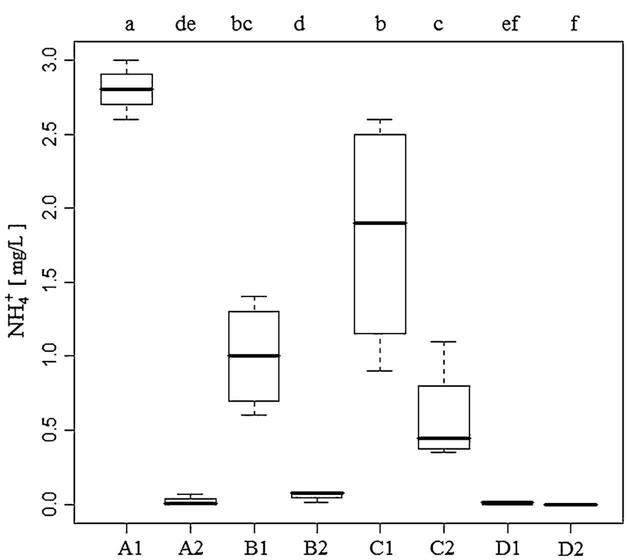


Fig. 17 Concentration of NH_4^+ in the water of the studied reservoirs. *A1* Grantz bottom layer, *A2* Grantz subsurface layer, *B1* Vycpalek bottom layer, *B2* Vycpalek subsurface layer, *C1* Vanek bottom layer, *C2* Vanek subsurface layer, *D1* Rampa bottom layer, *D2* Rampa subsurface layer ($n = 4$, sampling: April and November 2011, April and November 2012). Lowercase letters at the top of the figure indicate statistical difference at $p < 0.05$

from the catchment. The transformation of a holomictic reservoir into a meromictic type is dependent on a number of factors, among which the most important are: the capacity of the reservoir, the intensity of the organic matter supply from the catchment, the values of the depth indicator (Z_r), the surface area of the reservoir as well as the height of the rock walls of the excavation (conditioning waving). The phenomenon of meromixis in the studied reservoirs is permanent. Meromictic conditions were observed in 2011 and 2012 and also 2 years later—in 2014.

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