Findings from flooding residual pits remaining after coal mining in the Czech Republic

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Abstract

The work summarizes more than twenty years of experience in designing reservoirs in residual pits remaining after mining of brown coal in the Czech Republic, monitoring their flooding and development of lakes after filling. There are currently 3 artificial lakes in residual pits with a water surface of 225 to 496 hectares. In the future there will be another 5 lakes covering area in the range from 390 to 1,300 hectares. The beginning of their flooding is expected mostly after year 2035. Due to complete lack of natural lakes in the Czech Republic, the main expected use of these artificial lakes is recreation, including sport fishing.

Rehabilitation projects of mined areas are processed for many decades prior to the termination of mining. This planning gives the possibility to optimize the morphology of the residual pit with minimal cost. Subsequently, studies have repeatedly supplemented and corrected. However coal mining is currently associated with the risk of early termination of mining, when the residual pit does not have the optimal morphology. This also concerns all residual pits with regulated flooding in the Czech Republic.

The stabilization of residual pit slopes is associated with the greatest cost and problems, which are mainly the consequences of water saturation of soils that had been drained for decades. Especially expensive is the fortification of shoreline at the final water level. Abrasion during lake filling is confined to a strip not exceeding 2 m around the perimeter surface and does not affect the overall stability of the slopes.

For flooding the preferred option is water with the least contamination. There are enough data on the quantity and quality of water selected to flood the residual pits. On the contrary little data are available about the quantity and quality of water flowing from the slopes of the quarry. It is crucial for the development of the water quality of lakes in the period after of their filling.

Water quality is not a problem in the Czech conditions. The resulting pH of lake water in all cases is slightly alkaline. This, together with good oxygenation of the water leads to a drop in metal concentrations below the limits for surface water even during filling. Nowhere was found significant contamination by chemicals or bacterial contamination. Trophic state is adapted to the amount of inflowing nutrients and depth of reservoirs within a few months. Residues of mine water on the bottom of the pit cause short-term or long-term meromictic state. In one lake is formed near the bottom anaerobic state, which on the end of November, affects about one third of the lake area.

The concentration and species composition of plankton, benthos and fish is strongly influenced by very low water trophy. Problems with cyanobacteria water blooms were not observed and this situation is sustainable. Submerged vegetation develops rapidly and large reservoirs are attractive for water birds.

There is no clear definitive future owner of the lakes due to fears of the high costs associated with the maintenance of the lakes.

Key words: residual pit, lake, Czech findings

Introduction

Pits remaining after the surface mining of minerals are often spontaneously flooded by rain and by surface and underground water. Flooding sometimes occurs already during extraction, particularly in sand and gravel mining. In the Czech Republic there are tens of thousands of such flooded pits from the past. They usually cover a small area and the process of flooding was not regulated. Closing of large open pit lignite mines created the need for the controlled flooding because the spontaneous flooding would take many decades or even century. Controlled flooding is in accordance with Czech legislation regulating the extraction process and following recultivation of the territory after stopping of mining. It also ensures relatively rapid achievement of the target state and thus accelerates considerably the use of the resulting lakes. Controlled flooding also allows modifying some features of lakes according to their expected future use.

Currently there are in Czech Republic three lakes built in the brown coal residual pits with a water surface of 252 to 496 hectares. In the future there will be another 5 lakes with a surface ranging from 263 to 1,312 hectares. The beginning of their flooding is expected however mostly after the year 2035th. In the meantime it is convenient to sum up past experience and adjust projects of the flooding of other quarries accordingly.

History

In the Czech Republic there are many dozens of larger reservoirs formed by flooding pits after the open pit coal mining, which originated mainly after year 1945. Spontaneous flooding lead to creation of lake up to 60 hectares in size and over 50 m deep - Barbora near Teplice. This lake is extensively studied for 30 years and is the source of much valuable knowledge about the behavior of mining lakes. As a rule, however, spontaneously flooded lakes are significantly smaller and shallower, eg. water areas in the residual pits of former small surface mines Otakar, CSM, Liebig, Dukla near Teplice or Elizabeth near Most. The water quality of these lakes is much better than in ponds and dam reservoirs. Some lakes are meromictic with elevated concentrations of salts and some metals under chemocline. In general they are used for sport fishing and swimming.

Several smaller pits were flooded artificially. In the early 70s of the 20th century residual pit quarry Benedict in the vicinity of Most was filled and used as a natural swimming pool. But the bottom of the reservoir was not sufficiently sealed and it lost water. The reservoir had to be rebuilt and reduced, which was implemented in 1999. It now has a water area of 4.7 ha. In early 90s the site of a former quarry Vrbenský on the edge of the town Most was built and Matylda reservoir was artificially filled up and used for water sports. It has an area of 39 ha, but the maximum depth of only 4 m. If necessary, it can be drained. In 2002 additional reservoir in the residual pit mine Michal near Sokolov was artificially flooded. It has 30 ha and maximum depth of 5 m and can be drained if necessary, which has already been done twice. It serves as a natural swimming pool. The reservoir is currently inhabited with purposeful fish stock.

These shallow reservoirs have naturally higher trophic conditions than deep lakes. Water quality is monitored systematically only in the Michal reservoir. Although it succeeded in maintaining pure water with perennial transparency 3-5 meters without cyanobacteria, it is clear that eutrophication of the reservoir is uncomfortably fast. Without the fish stock, its biocenosis develops highly unpredictable and there are various problems that must be solved operatively: mass reproduction of toads, macrovegetation overgrowing, Swimmer's Itch, etc. Specialized fish stock must be chosen very carefully in order not to cause excessive release of nutrients from the bottom to the water column.

Some residual pits were or still are used to store fly ash. This is not their final state and falls outside the focus of this work.

Since the last decade of the last century there were closures of big mining quarries with pits large enough to enable creation of lakes up to 1,300 ha in size with a maximum depth of 200 m. For these potential reservoirs, controlled flooding is part of the reclamation of the entire mining area. In early 90s of the last century there was a broad initiative addressing the selection of optimal recultivation method for the post-mining territory. The possibility of filling these pits with waste material stored in dumps was dismissed as economically and ecologically unfavorable. Instead, the initial recommendation was to build shallow and flow reservoirs. Based on limnologic theory the contrary was justified - that to achieve good water quality the lakes should be as deep as possible and with little flow. The need for a thorough isolation of coal seams from the water column has proved unnecessary. To achieve stability of the bottom rapid filling with water in 4-8 years was advised even for the biggest pits. This approach has been used for the controlled flooding of three residual pits: Chabarovice (Milada), Most and Medard. Findings presented in this work are based on lessons learned from their flooding. Table 1 gives an overview of lakes in large residual pits after mining with the currently considered parameters.

Table 1 *Overview of lakes in large residual pits in Czech Republic.*

quarry name	water area (ha)	altitude (m)	volume (10^6 m^3)	mean depth (m)	maximum depth (m)	start of flooding year	end of flooding year
existing lakes							
Chabarovice	252,2	145,7	35,6	14	25	2001	2010
Most	309,4	199	70,5	23	75	2008	2014
Medard	495,8	400	119	24	50	2008	2016
planned lakes							
CSA	666,1	180	270,3	41	130	2026	
Bilina	930,6	200	706,1	76	200	2038	
Libous	939,8	275,2	235,7	29	76	2038	
Jiri	1 312,3	394	514,9	39	93	2038	
Vrsany-Sverma	263,5	206	44,8	17	40	2050	

Projects of controlled flooding

Flooding of residual pits is solved individually for each quarry within the Reclamation Plan, which is an integral part of the so-called Plan of opening, preparation and extraction. On this basis the license for mining activities in accordance with the Mining Act is issued. Water management solution of residual pit flooding is usually progressively refined by updates of so called General plan of remediation and reclamation, which solves the overall concept of rehabilitation and reclamation of areas affected by mining. Implementation of the project of the final site remediation precedes the EIA process.

Viable project should contemplate and if possible incorporate various alternative uses: recreation, quality water source, pump storage plants, fishing, retention of flood waves, bird reserve etc. Because of the complete lack of natural lakes in Czech Republic, the use of mine lakes primarily for recreation, including sports fishing prevails. No project is currently aimed at using these lakes for protection against flood.

The first study of reclamation is prepared decades before the termination of mining. This theoretically allows even during mining itself to cheaply optimize the final shape of the residual pits mainly in the areas of future shoreline. Reclamation projects are associated with considerable uncertainties especially in extent of mining. Gradually they are updated and refined. The greatest risk is currently a sudden early termination of mining, resulting in suboptimal morphology of residual pit. This has occurred in all still controlled flooded residual pits. The reclamation projects solve the slope stability, bottom sealing, fortifications of coastal line, colliding with underground mining, the amount of water needed for flooded pits, spreading capacity of water resources and their quality. Prediction is made of the water quality immediately after filling of lakes and its further development. An effort to reduce the cost of reclamation leads to the assessment of variants with reduced water levels, which is inconsistent with the optimal solution to the future lakes with long term benefits.

Experiences with controlled flooding of pits

The water quality is monitored in detail by mining organizations during filling and the monitoring continues even after filling. Independent monitoring was conducted in the framework of various research projects. These lakes will become independent artificial water bodies of stagnant water under the Framework Directive of the EU water policy. At present there are filled lakes also monitored according to the requirements of this Directive. Development of water quality and biota of artificial lakes, especially during relatively long flooding, differs from new dams and natural lakes with steady conditions. From this perspective, this monitoring and its findings stimulate the development of hydrobiological theory. The topic of residual pits flooding in the Czech Republic has been repeatedly presented at IMWA conferences (e.g. Svoboda et al. 2008; Vrzal et al. 2011; Prikryl, Spacek, Koza 2011; Peterka et al. 2011; Peterka, Kubecka 2011). Results of a broad-based project investigating the flooding of Most lakes are published eg. in the works Rehor , Frastia , Schmidt 2013 and Vagnerova, Svoboda, Brejcha 2013. Much of the data is in non-public reports to the mining companies.

The monitoring of all three still flooded large residual pits shows that the predictions of their water quality were generally successful. We were unable to predict only the emergence of chemoclines in two lakes and high concentrations of some substances in the oxygen-free water layer under chemocline. Water under chemocline at greater depths, however, is well insulated from higher layers and does not significantly affect its chemistry. Water under chemocline represent only a few percent of the lake volume and is usually located in depressions on the bottom. If necessary, the chemocline can be inexpensively eliminated. Formation of long-term stable chemoclines can prevent the inclusion of local depressions in the bottom of quarry before flooding.

The quality of water in the upper stirred layer corresponds well to expectations. This is confirmed by extensive monitoring of all three lakes. In comparison with the quality of the inlet water the concentration of nutrients quickly decreases, so lakes are oligotrophic usually already during filling. Small production of live biomass allows for maintaining high concentration of oxygen in the water column with the partial exception (Lake Chabarovice) described below. The catchment area of the lake itself, i.e. slopes adjacent quarries and dumps, consists of impermeable clay soils with weak erosion. Some of the springs on the slopes of quarries may be enriched with metals, and thus contribute to their concentration in the lakes in the long term. However, the share of acid water is small and the resulting mixture of water from its own catchments area has an alkaline pH. The combination of high oxygen concentrations and sufficiently high pH leads to a rapid decrease in the concentration of metals. Selected organic toxic substances (in the lake Chabarovice approximately one hundred substances) in water and sediment were also monitored. No measurement of these substances exceeded applicable limits. For all currently flooded residual pits the high water transparency is adequate - in the summer from 5 to 10 m, in winter even higher.

During the flooding there were some unforeseen problems that have raised fears of mining organizations regarding meeting the conditions of required water quality: increased turbidity of water in the initial period of pits flooding, oxygen deficit in the metalimnion during heavy inflow of river water, high concentrations of nitrates originating from reclaimed areas, high concentrations of chlorophyll in metalimnion, the stratification of dissolved substances and complicated vertical structure of their concentration. These problems have been explained and during flooding mostly disappeared.

Most of the pits in the Czech Republic are in an area with a lack of rainwater and without major rivers. Great attention is therefore paid to the water sources for the flooding. Preferred are waters with the least pollution, which is a certain problem of mining areas. Nevertheless, there are sufficient data on the quantity and quality of water selected for the flooding of residual pits. On the contrary, there are little data on the quantity and quality of water flowing from the slopes of quarries. That over several decades will replace the water from an artificial source. It will then be crucial for the development of water quality in lakes in the period after the flooding. These waters sometimes have a high salt concentration and enormous concentrations of metals. Their quality after termination of mining is changing quite rapidly, which complicates forecasting the development of water quality in lakes. A separate problem is discharging sewage from the expected intense recreation outside the lakes.

Even with an overall excellent quality of water-filled mine lakes, some indicators will exceed the current limits for surface water. This concerns in particular dissolved substances and sulfates, sometimes calcium or magnesium. Exceeding the limits in this case is not a sign of water pollution because it is in these conditions a natural state. It would be desirable that these properties of lake water also take into account the Government Decree on the values of permissible pollution of surface waters.

Protection of buildings constructed during the existence of the quarries below the original level of ground water forced the reduced levels of water compared to natural levels in lakes Chabarovice and Most. It has certain negative implications for the water quality. Chabarovice Lake has an average depth of only 14 m. The result is a very small volume of the layer called the hypolimnion, in which oxygen enters only in the circulation water in the cold season. Although the lake is oligotrophic, there is not enough store of oxygen to the mineralization of organic matter falling from the upper layers of water. Oxygen deficit is increasing gradually during the year from greatest depth. In November, before re-mixing the entire water column anoxia will hit bottom about one third of the lake. The concentration of iron, manganese, ammonia nitrogen and total phosphorus increases in oxygen-free water. The lake is under permanent threat of inner eutrophication, which would greatly deteriorate water quality for recreation. Lake Most was built as endorheic due to reduced water levels. The level is chosen so as to compensate for the inflow and evaporation and minimal enough water filling from external sources or occasional pumping to maintain the level of the selected range. The lake has a sufficient depth so there is no risk of internal eutrophication. However, water with increased concentration of dissolved substances flows into the lake from its own watershed and these substances are concentrated in the lake due to evaporation. Unlimited growth of solute concentration in the longer term could degrade the water for recreation. It will therefore be necessary to ensure greater exchange of water than is sufficient to maintain normal water level.

The concentration and species composition of plankton, benthos and fish in large residual pits are strongly influenced by very low water trophy. The amount of planktonic organisms is very small and their species communities are rather poor in comparison to the dam reservoirs and ponds. No problems with cyanobacteria water blooms have been reported to this date and this situation is sustainable. Monitoring has demonstrated surprisingly high species richness of benthic organisms, for instance 17 species of aquatic mollusks in the lake Chabarovice. Submerged vegetation develops spontaneously relatively quickly, mainly due to the high transparency of the water. Rare and protected species, especially those with high demands for clean water are also present already in the first years of flooding. Large reservoirs are attractive for water birds, although they do not have sufficient food supply. Waterfowl are potentially a significant source of eutrophication of these reservoirs. Incidence of non-native species of plants and animals was also reported, but it poses no significant risk for the lakes. Mining lakes do not meet the needs of anglers. Due to the low trophic conditions of lakes fish stock reaches approximately 10 kg / ha, at most several tens kg / ha. This can be partially compensated by the occurrence of a record size fish, which is the common in many small spontaneously flooded residual pits. Anyway sport fishing in these lakes will have to be very carefully regulated.

Water quality in terms of various indicators can be evaluated as very good and no action to improve it was required yet. The same cannot be said about the technical reclamation. Experience shows that the greatest costs and challenges are associated with residual pit slope stabilization. These are mainly the consequences of water saturation of soils, which were drained for decades. Planned recreational operation of filled lakes can be delayed for years due to the need for slopes stabilization. Sealing the bottom of pits is costly, especially if it threatens to flood the underground space with still active mines. Especially expensive is the fortification of shoreline at the final water level. Fortification is done for the minimum water level fluctuations (usually plus or minus 0.5 m). Greater fluctuations in the water level or even a small change of level compared to the project necessitate larger fortifications. The impact of coast abrasion during flooding of the lakes is noticeable already after several centimeter change of water level. Abrasion is confined to a strip not exceeding 2 m along the perimeter surface and does not affect the overall stability of the slopes. Therefore the limited extent of damage caused by abrasion is not the reason for fast flooding of lakes. It is thus possible to save considerable costs associated with building the capacity of supply channels and pipes or buying water pumped to remote locations.

There are high expectations associated with the lakes originated by coal mining, because there are no large natural lakes in the Czech Republic, where it would be possible to do water sports. Several small mountain lakes are part of a protected area with restricted access. Another favorable aspect is the predicted and documented excellent water quality in mining lakes in comparison with dams and ponds. Grandiose ideas arose about the extent of recreation on lakes and their surroundings. The adjacent large cities as well as smaller municipalities showed initially great interest in operation of these reservoirs. The problems with the stability of the pit slopes and costs associated with troubleshooting cooled this enthusiasm considerably. Municipalities are now reluctant to take ownership of the ready-made lakes, because they fear the costs spent on their maintenance and payments for water required for their recharge. They are unsure of their ability to meet the conditions of handling regulations. Strict legislation on the quality of surface water and lack of professionals in the municipalities with understanding of this issue undoubtedly contribute to these concerns. State-owned enterprises which take care of the streams and dams, are not interested in the management of these lakes either, because they are not their usual source of revenue that are the water sale and electricity production. These companies do not have the promise of state funding necessary for the lake maintenance, as they are used to receive for watercourses. Maybe this situation will extend the existence of the residual state enterprise, which ensures the completion of reclamation of old mining areas and currently employees group of experts knowledgeable in the mining lakes subject. This applies to lakes Chabarovice and Most. Lake Medard remains owned by a private mining company Sokolovská uhelná, which plans the use of land in its post-mined territory in the future. This company already operates Michal reclaimed pit lake used as a natural swimming pool. Therefore there should be no issues with the operation of this lake. Currently we are awaiting the first major investment in sports and leisure facilities in filled lakes which would be inspiration to other investors. Lakes definitely have the potential to generate enough money for their maintenance from these activities.

Conclusions

For practical reasons, the residual pit should be flooded soon after extraction to accelerate the start of their expected usage.

The water should preferably be at the level of the surrounding streams so that excess water can be drained by gravity. Alternatives with reduced levels lead to the need for costly long term water pumping, which also causes water quality deterioration. Lakes with a strongly recessed surface are poorly usable for recreation.

It is advisable to design either relatively shallow lakes with an average depth of 6 m (a maximum depth of about 15 m) or vice versa deep lakes with an average depth of over 20 m (maximum depth over 50 meters). In lakes with an average depth of about 6-20 m, hypolimnion with a small volume and inadequate supply of oxygen is formed. The result is the emergence of annual anaerobic layers at the bottom and a strong tendency to internal eutrophication.

It is not necessary to rapidly flood the lakes, originally justified by the fear of abrasion shores. Conversely, it is possible to save considerable costs associated with building a capacitive supply channels and pipes and pay for the water that must be drawn from streams. Use of less abundant streams from which water flows to residual pits by gravity is more cost efficient.

For good properties of the lakes, unscheduled early termination of mining activities that does not allow for proper shaping of the residual pit is a particular risk. Subsequent landscaping is much more expensive. Big problems associated with improper morphology of residual pit will probably arise in quarry CSA unless the so-called territorial environmental limits are exceeded.

If formation of chemocline and meromixis would be assessed as undesirable in the future, it is possible to significantly reduce their occurrence by filling depressions at the bottom of the quarry.

Phosphorus as a main limiting nutrient gets to water reservoirs through different ways. Only a very small proportion of phosphorus flows away from the reservoirs or escapes. Water reservoirs are therefore gradually eutrophicated; in contemporary eutrophic cultural landscape uncomfortably rapidly. Supply of phosphorus during flooding can be quite precisely assessed depending on the quality of water from different sources. In contrast, the sources of phosphorus after flooding can only be estimated on the basis of current knowledge and their balance is very inaccurate. Data to support measures to slow eutrophication are unfortunately not abundant. Research on this issue in the conditions of Czech coalfields is therefore very necessary.

During the flooding of other residual pits greater attention should be dedicated in time to the balance and quality of water flowing from its own catchment. Its influence has been underestimated so far. However, in a long term perspective, it will determine the quality of the lake water virtually in all quarries.

In the ongoing evaluation of data acquired by monitoring it is necessary to take into account the changing characteristics of lakes during the climb levels and already identified patterns of the various stages of flooding. It is to be expected that despite the overall excellent quality of water, several indicators may not meet the normal limits for surface water in the whole volume of the lakes or more frequently in a specific water layer. In whole volume it is mainly a solute, sulfates and sometimes calcium or magnesium. Under eventual chemocline the limits for surface water may be greatly exceeded and for more substances then in the whole volume, as well as concentrations of some metals and ammonia nitrogen and moreover deficiency of dissolved oxygen. Oxygen deficit can occur temporarily during flooding and persists for some time after flooding even in the upper water layers. The pH limit may be breached in some lakes in the summer due to photosynthetic activity of macrovegetation. In all these cases exceeding the limits does not adversely affect the anticipated use of lakes, i.e. recreation and recreational fishing. The high pH value is not the indicator of pollution in this case, but the natural property of waters in the catchment area of lakes in the residual pits.

Irrespective of the previous comments, good quality of water suitable for the needs of recreation and fish life, exceptional for the usual conditions in the Czech Republic, can be realistically expected in these new lakes. Most of the lakes will be very resistant to the effects of eutrophication. The mass development of cyanobacteria algal bloom, which is in recent decades a major problem in today's recreational vessels, is not a threat in these lakes. Flooded residual pits will hold large strategic reserves of high quality water, which at the appropriate management can be pumped from new lakes also for other uses. These lakes will be undoubtedly beneficial to the biodiversity as well. The new artificial lakes can certainly serve these and other functions with minimal maintenance costs for hundreds or thousands of years.

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