Mining Lakes: Generation, Loading and Water Quality Control

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1 Hydrography and Geology in Relation to Water Quality

During the surface mining process the overburden layers tend to become mixed and former aquifers destroyed or at least heavily changed. With current technology, the quaternary and tertiary layers above the coal seam are cut in by bucket wheel excavators and transported by a conveyor belt bridge into the empty part of the mine. Other excavators take off the lignite layer for transportation out of the mining hole. The volume of a potential mining lake resulting from this process is the deficit from the removal of coal. Sometimes the volume is smaller, because the ash of the coal, burnt in nearby thermal power plants, or overburden of other newly opened mining sites is dumped in the mining hole.

Today, the opencast process starts with dewatering the whole mining area down to the layers under the coal to be mined. By a series of wells and well batteries the water table is lowered in order to dry out the lignite so as to improve its burning value. Depending on the local conditions the ratio of withdrawn water to extracted lignite may be from 100 % to more than 1000 %.

The hydrologic conditions in rivers and drainage basins are heavily disturbed from the early beginning of preparation of an opencast mine. Larger rivers crossing the mine site have to be transferred into new canal beds surrounding the site and, being unnatural, tightened to avoid seepage of water into the dewatered underground. Smaller rivers and creeks and wetlands become dry. In connection with the geogenical acidification of future mining lakes, the change of the redox-potential in the underground is of special interest. Upon dewatering, the sulfur-containing minerals pyrite and marcasite come into contact with air and therefore with oxygen, instead of oxygen-poor groundwater. Before and during the mining operation, the virtually continuous addition of groundwater into nearby rivers causes unnatural balanced throughflow. No typical low water situations occur for the decades of mining activities. In addition, the water temperature is more balanced by the groundwater influx. Within the long time span of a mining operation, the water balance of the whole landscape, with its forests and wetlands, as well as the water users and water management, must adapt to the changed hydrology. In Germany, a typical case is the mining region Lusatia and river Spree. Mining operations have affected a remarkable and unique wetland called Spreewald and downstream Berlin's largest drinking water treatment plant at lake Müggelsee, fed by the river Spree.

Rapid closure of many mines after German unification introduced, within a short time, challenges of satisfying the water demand for filling newly forming lakes and for refilling the groundwater deficit around the open air mining holes. The volume of the emerging 160 mining lakes amounts to 7.5×10^9 m^3 and the deficit in the emptied groundwater layers is 13.5×10^9 m^3. Together the total water demand is 21×10^9 m^3 (Ziegenhardt 1994).

By 1990 about 2500 km^2 of land was impaired by a lowered groundwater table. Now the active mining is concentrated at only a few sites and the decreased groundwater abstraction may lead to some complications for Berlin's water supply and the wetland-ecosystems of the Spreewald. Several of the new mining lakes are, therefore, being developed as reservoirs for water storage, with inlets and outlets constructed. This way, low water enrichment is possible, to avoid or to minimize the negative effects during the time of readjustment to the natural water balance (Ziegenhardt and Trogisch 1996).

Those lakes emerging in the recent, largest open pits will, in particular, exceed many of the desirable hydrological characteristics of the majority of the natural lakes in the Baltic region of northern Germany. The mining technology creates hollows with relatively steep slopes. Therefore, the bioproductivity of the littoral zone in subsequent generated lakes is low. Also, in the first year of existence, the beds of mining lakes typically consist of minerals with a very low content of organic matter. A couple of years is needed until the layers of sand and coal on the bottom are covered by dead algae, forming the typical "gyttja"-mud, well known from natural lakes where it serves many animals as a habitat and food source.

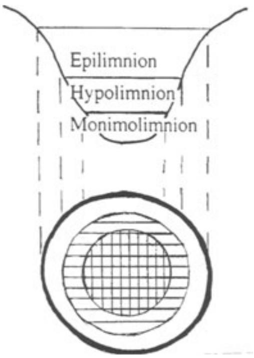
Table 1. Mining holes in eastern Germany to be flooded within the few next years. Group 1 with mean depth > 15 m according to hydrological class 1; group 2: 10 to 15 m according to class 2 of standard TGL 27885/01 (after BLAG 1994)

Mining lake Group1	Volume [x 10^6 m^3]	Area [ha]	Mean depth [m]
Berzdorf	387	950	40.7
Nachterstedt	226.3	630	35.9
Klinger See	102	300	34.0
Greifenhain	330	973	34.0
Spreetal-NO	97	314	30.9
Cospuden	107.6	393	27.4
Espenhain-Störmtal	154.6	560	27.6
Espenhain-Markkleeberg	65	250	26.0

Table 1. (continued)

Gräbendorf	93	412	22.5
Geiseltal	409	1890	21.6
Zwenkau	188	900	20.9
Kleinleipisch	23	124	18.5
Ilsesee-Meuro	134	754	17.8
Restsee Scheibe	133	714	18.6
Gröbern	70.4	400	17.6
Witznitz II-	97.8	560	17.5
Merseburg-Ost	82.5	520	15.9
Wulfersdorf	22	141	15.0
Group 2			
Witznitz II Kahnsdorf	17.7	120	14.8
Bärwalde	14.8	1017	14.6
Holzweißig-West	23.3	160	14.6
Goitsche	217.5	1500	14.5
Kayna Süd	28	200	14.0
Breitenfeld	27.5	200	13.8
Königsaue	30	220	13.6
Skadoer See	130	980	13.3
Bergheider See	38	290	13.1
Rösa	97	750	12.9
Spreetal-Bluno	152	1211	12.6
Dreiweibern	35	286	12.2
Drehnaer See	17	142	12.0
Sedlitzer See	141	1311	10.8
Golpa Nord	66.1	620	10.7
Lichtenauer See	25	234	10.3
Lohsa II	99	958	10.3
Bockwitz	19.0	187	10.2
Werben	9.1	90	10.1
Burghammer	43	432	10.0
Olbersdorf	6	60	10.0

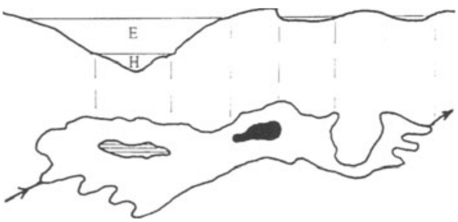
Regarding the utilisation of water for drinking, fisheries or recreation, the lakes of special interest are those which possess, from the beginning and also in future, a sustainable good water quality. One of the most important prerequisites for developing this type of "clear water lake" is a great depth. In Table 1 the newly forming German mining lakes are arranged in order of their mean depth. Those with more than 15 m depth have the potential to be class 1 and those between 10 – 15 m to be class 2 according to the German TGL 27885/01 (1982) standards. In principle, there are two different options for developing mining lakes. From an human view the lake should contain the cleanest water possible, so it is suitable for purposes such as drinking water, bathing, or fisheries (Fig. 1 and Table 2). However, with respect to nature protection and landscape formation, quite different targets will be set. Because of the general agricultural overproduction in the European Union there is no pressure to obtain maximum yield from each hectare of land. Therefore, some of the new mining lakes may be developed only to provide interesting parts in the landscape, with a high diversity of biological species. To meet this target, a very diverse morphometry of the new lake has to be established. The lake should possess deep as well as shallow parts, a long shoreline relative to the lake area, bays, islands, a mixture of steep and shallow banks etc (Fig. 2). In this way many diverse habitats for different plants and animals are available. In the case of a lake with no human use or special water quality demands, a higher bioproductivity is no disadvantage. In other cases the environment might even remain in an acidic state without fish, mollusc or higher crustaceans and, nevertheless, be an interesting object of limnology with respect to conditions in extreme habitats.



- great depth
- very large ratio of hypolimnion to epilimnion volume
- stable stratification
- steep shore
- small part of the benthos belongs to the epilimnion
- low shore development
- small nutrient import (inflow)
- lake bottom with phosphorus binding matter
- low nutrient recirculation

Water suitable for very demanding water uses: Raw water for drinking and process water, bathing, diving, coregonid fishery

Fig. 1. Hydrography and quality factors for low productive clear water



- shallow depth
- small ratio of hypolimnion to epilimnion volume
- lake bottom is mainly in the epilimnion
- very shallow banks
- considerable shore development
- diverse morphology
- high nutrient inputs
- high nutrient recirculation

Water unsuitable for demanding uses. Water body suitable for nature protection and as parts of the landscape worth seeing

Fig. 2. Hydrography and quality factors for high bioproductivity and high species diversity

Table 2. Characteristics of a clear-water lake with low bioproductivity

Hydrography	Chemistry	Biology
large mean depth	poor in macronutrients: P, N, Si	low primary productivity
large maximum depth	precipitation of P with binding cations Fe^{3+}, Al^{3+}, Ca^{2+}	limitation of indispensable resources: light, P, N, Si (at pH < 3 also DIC and DOC)
large lake area	matter flux directed to the sediment	at pH < 3 all species that need carbonate and hydrogencarbonate are excluded
large lake volume	low import of matter	phytoplankton is curbed by
Small drainage basin	matter export high	• sinking losses in macrophyte standings • grazing losses • biogenic calcite precipitation • flushing losses
few inhabitants, or equivalents, in the drainage basin	binding to permanent sediment greater than redissolution	
extensive utilization of the drainage basin	hypolimnion aerobic	
steep shore slopes	stable fixation of phosphorus in oxic sediments	
small part of the bottom belongs to the littoral zone	with pH < 3 no HCO_3^- and CO_3^{2-}	bioflocculation of bacteria and colloids
minimal bank development	toxic influence of acid-soluble heavy metals (?)	low biodiversity
stable stratification		
water exchange only with groundwater		

2 Water Origin: Quantity and Quality of Ground and Surface Waters

Tables 3 and 4 list the advantages and disadvantages of filling mining holes with ground and surface waters. In regions where the lignite and overburden have a low sulfur content and possess enough carbonate hardness for neutralisation of occasional geogenically caused acidification, groundwater is best suited as the filling water for generating a lake. Use of groundwater guarantees a lake with sustainable good water quality, i.e. low bioproductivity and high resistance against eutrophication and its impairing consequences (Table 3). Some of the disadvantages of groundwater filling may be avoided. Instead of flooding with the very slowly rising underground water at the site, additional groundwater from the dewatering of active mines, not too far distant, may be used. However, this foreign water has to be analyzed and its suitability confirmed. Excellent groundwater may be obtained from the dewatering before mining. The wells in the undisturbed rocks in general contain circumneutral waters, sufficiently buffered by carbonate hardness. The phosphorus and heavy metal contents are low. Rapid flooding with such neutral groundwater, so that the water table in the lake rises faster than in the surrounding underground, seems to be the most beneficial solution.

This practice has been utilized in the lignite mining region south of Leipzig, Germany. Instead of filling with river water from the Weisse Elster, the quality of which would have been suitable only after a treatment, a 23.5 km long pipeline has been built. Currently, the pipeline delivers a flow of 45 m^3/min, from the active mine Profen, to flood the former mine Cospuden. The pipe system will be extended to 70 km and completed with side branches in the coming years to fill the mining holes of Markkleeberg, Haubitz, Hain, Störmthal, Werben and Zwenkau (Fig. 3, Zeh 1998).

Table 3. Advantages and disadvantages of filling the mining hole with rising ground water

Advantages	Disadvantages
Provided sufficient bicarbonate, the rising groundwater is poor in phosphorus, which is bound to Fe^{3+}, Al^{3+}, Ca^{2+} and clay minerals	Filling times are extremely long in extended dewatered mining sites and with locally destroyed aquifers
Low organic mother load is responsible for poverty of heterotrophic (and pathogenic) germs	Hydraulic gradient from a higher groundwater table in the surrounding to the lower lake surface endangeres the stability of the slopes
Metal hydroxides are precipitated in the lakes; phosphorus and bacteria are transferred with the precipitates to the bottom sediment	Pyrite is oxidized in the area of groundwater exfiltration, especially in the overburden heaps. Sulfuric acid together with acid-soluble metals impair the water quality
Favourable trophic state for many years, relating to the morphometry	Geogenically acidified waters are not inhabitable for many organisms including fishes
If not impaired by acidification, the water is qualified for particular demanding utilization from the beginning of the filling process	After neutralization, the previously dark-red, dissolved ferrihydroxide of acidic lakes precipitates as ochre coloured turbid flocs. This ugly stage of succession towards more nature-near conditions may last for decades of non-usability

Table 4. Filling the mining hole with river water

Advantages	Disadvantages
Quick flooding possible; fishes survive from the first filling stages	Many running waters are highly loaded with nutrients, oxygen consuming and hazardous substances
From the first flooding neutral and relatively poor mineralized water	Poor trophic conditions exist in the first years, relating to the morphometry.
Hydraulic gradient from the higher lake level to the lower groundwater table stabilizes the slopes	Loading of the surface waters may be introduced into the groundwater space with the danger of irreversible damages

Table 4. (continued)

By oxygen-consuming substrates, the underground environment becomes anoxic and metals are immobilized in sulfidic form; the pH of the groundwater rises	Mass development of algae, because of eutrophication, impairs the recreational water utilization
By incorporation in algae biomass and sedimentation, nutrient and hazardous substances are transferred permanently into the bottom sediments	Oxygen depletion in deep water layers reduces the habitat for fishes and their food animals
Not so demanding utilization (e.g., watersport without body contact with the water) is possible at an early stage	Especially in the first years, technological requirements to improve the water quality by treatment of filling water or by in-lake ecotechnologies

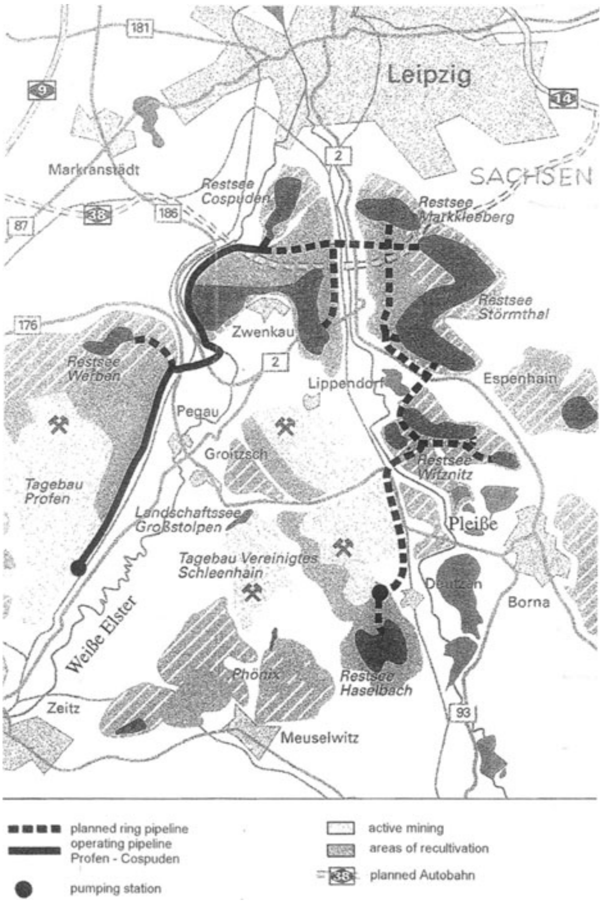


Fig. 3. Concept for flooding mining lakes south of Leipzig, Germany (from Zeh 1998)

The flooding of mines with surface waters may be undertaken either for filling purposes only or alternatively to give a partial or fully permanent throughflow. An example of the latter case is the Mulde Reservoir near Bitterfeld, Germany. The former mining hole Muldenstein now functions as a river water treatment plant. The diverse water quality parameters are eliminated with varying efficiency. This depends on the behaviour of the matter with respect to adsorption, sedimentation, introduction into nutrient chain and metabolization or bioproduction of autochthonous biomass and photosynthetic oxygen (Table 5).

The effect of the Mulde Reservoir in Germany is comparable to that of a pre-basin to a drinking water reservoir, protecting the main basin against the import of unwanted matter (TGL 27885/02 1983). On the eastern bank of the Mulde Reservoir, which consist of loose rocks from old overburden heaps, are many sources of acidic waters with high contents of dissolved iron. Mixed with the neutral, bicarbonate containing reservoir water, ferric hydroxide is precipitated, obviously together with phosphate.

Therefore, the reservoir may be compared not only with a pre-basin, but also with a phosphorus-elimination plant in which phosphorus is separated by sedimentation and deposition on the bottom of the water body. Together with the settling matter, bacteria may also be transferred from the water into the permanent bottom sediments. Consequently, the outlet of the Mulde Reservoir is more appropriate for lake filling water than the Mulde-river upstream. Therefore, since 1998, filling water has been taken from the outlet of the reservoir to flood the various basins of the big mining complex Goitsche near Bitterfeld, within a short time period.

Table 5. Mining lake Muldestausee, Germany utilized as a as river water treatment plant (yearly means from Gewässergütebericht Sachsen-Anhalt 1992)

Criteria	Inlet samples	Arithmetic mean	Outlet samples	Arithmetic mean	Elimination [Inlet = 100 %]
suspended matter [mg/l]	25	17.2	25	2.3	86.6
inorganic nitrogen [mg/l]	25	6.5	24	6.1	6.15
orthophosphate-P [mg/l]	25	0.260	25	0.174	33.1
total phosphorus [mg/l]	22	0.924	22	0.378	59.1
oxygen [mg/l]	25	10.2	26	11.0	7.84
O_2-saturation [%]	25	90.0	26	99.0	10.0
BOD_5 [mg/l]	25	4.9	26	4.1	16.3

Table 5. (continued)

chem. oxygen consumt [mg/l]	19	6.2	17	4.8	22.6
chem.oxygen demand [mg/l]	24	20.4	24	14.8	27.5
total organic carbon [mg/l]	12	7.6	12	6.1	19.7
total zinc [µg/l]	13	136.0	13	85.0	37.5
total copper [µg/l]	13	7.6	13	3.8	50.0
total cadmium [µg/l]	13	2.6	13	1.5	42.3
total iron [µg/l]	13	660.0	13	242.0	63.3
total manganese [µg/l]	13	205.0	13	155.0	24.4

The bottoms of the two northern basins Niemegk and Mühlbeck in the Goitsche mine/Germany consist of pyrite-rich amber sands, containing a high acidification potential. The possibility of acidification of the newly forming lakes in the region was estimated after soil and water monitoring, several elution experiments, computation and modelling. Depending on the depth of the acidity exchange at the bottom, the acidification may be stopped during the first flooding. If this is not the case, some special measures against the acidification must be performed. It should be mentioned, that the buffering capacity of the Mulde river is relatively low, due to low carbonate hardness (Kringel et al. 1997, Kringel 1998).

The following water quality problems have to be considered, according to the origin and kind of the filling water, the shape (especially the depth) of the lake basin, its position within the regional groundwater field and the nature of the geological substratum (Fig. 4):

1. Acidification is the most severe problem in connection with groundwater filling, especially in regions with sulfur-rich lignite, as in the case of the Lusatian mining district of Germany. Due to the oxidation of pyrite and marcasite, not only has low pH been observed, but also a high content of iron and manganese and, if present in the rocks in question, other metals. The report focuses on this problem in Chapter "Loading of Mining Lakes and Water Quality Control. 1 Acid Mining Lakes".
2. Salinization is important when mining is performed in close proximity of tertiary lignite and salt layers. The mining lake Merseburg-East in Germany had deep waters containing three-fold the oceanic concentration of sodium chloride. Currently the concentration is two-fold. Within the deep water, of high specific density, lignite particles are free floating rather than settling to the bottom.
3. Contamination with hazardous substances may occur when the open-air mine had been used as a dumping site for industrial or urban wastes, when

surface water used for filling is polluted or when geogenically acidified ground water dissolves heavy metals on its way through the overburden heaps.

4. Eutrophication is the main problem when the pit becomes filled with nutrient-rich surface waters. Algae mass development and turbid water in a mining lake restrict its use for most purposes. However, as shall be discussed later, in the case of acidification a controlled addition of eutrophying phosphate may shorten the succession from acidic to neutral lakes.

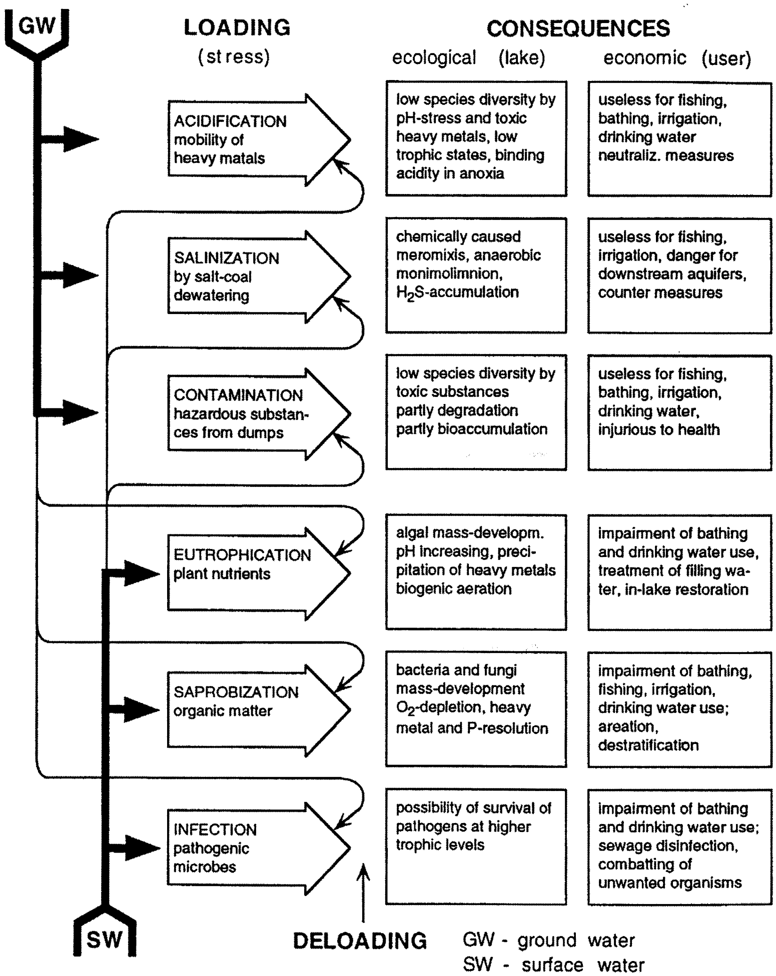


Fig. 4. Types of loading and consequences in mining lakes filled by ground (GW) and surface water (SW) (from Klapper et al. 1996)

5. Saprobization, i.e., loading with allochthonous and autochthonous degradable organic matter, is actually of lesser importance, at least in Germany. The water quality of the rivers used for filling has improved during the last years due to higher standards of sewage treatment. Waste is no longer dumped into mining holes because coal processing industries have been closed.
6. Infection with pathogens is related to the pollution of the filling waters and distinct types of water utilization. Duck feeding on a mining lake precludes bathing, because of *Salmonella* infestations.

Mixing of ground and surface waters allows considerable control of water quality in the lake. To abate eutrophication, a high percentage of groundwater is needed in the filling of the lake. With a content of cations such as Fe^{3+} and Al^{3+}, phosphorus will be bound and transported to the bottom sediments. Similarly, contaminants and bacteria may be adsorbed and precipitated.

In the case of the eutrophic mining lake Kayna-South in Germany, iron-rich groundwater is added and mixed using deep water aerators. Decreasing concentrations of phosphorus have been recorded. The "mesotrophy" water quality target should be achieved upon reaching the final water level.

Conversely, when adding surface waters, salty water may be diluted and acidic waters neutralized by carbonate hardness. The Lusatian lignite district is especially affected by geogenic acidification. Consequently, filling with river water was elected as the main way to cope with the problem.

The large opencast holes around Lauchhammer, Senftenberg, Burghammer and in the Schlabendorf district of Germany are presently being filled with uprising acidic groundwater. Values of pH less than 3 and high base binding capacities call for urgent action. Construction of pipelines is necessary, to allow filling with surface waters. This would achieve a water mixture with diminished acidity, and would stop further acidity influx, by forming a lake level higher than the surrounding groundwater table.

3 Living Conditions in Mining Lakes

3.1 The Chemical Environment

Compared with natural (glacier) lakes, the chemical environments of mining lakes, in the first years of their existence, are more influenced by the geological surroundings, the shape and size of the hole, the origin of the filling water, relatively high salt contents, and especially sulphate and heavy metals.

The mining lake bottoms mainly consist of minerals with low organic carbon, but with high phosphorus binding ability. There is only little growth of bacteria and algae on the bottom and nearly no closed biofilm for biological self-tightening against the surrounding groundwater. In the case of bank filtration for drinking water purposes, particulate matter, such as algae, pass through the biologically inactive sand layers of the shore and appear unwanted in drinking water. The consequences of different types of loading have been discussed earlier. The most important influence on the aquatic environment originates from geogenic sulfur acidification. The main processes are as follows: An initial weathering of iron-disulphide occurs with the first direct contact of pyrite-containing layers with the air (and water):

$$FeS_2 + 3.5\ O_2 + H_2O \Rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$

The Fe^{2+} ions are further oxidized to Fe^{3+} by air-oxygen:

$$Fe^{2+} + 0.25\ O_2 + H^+ \Rightarrow Fe^{3+} + 0.5\ H_2O$$

This reaction is strongly accelerated by microorganisms of the type *Thiobacillus ferrooxidans*. The next step, the formation of ferrihydroxide, takes place mainly at the transition from the heaps to the open water and is connected with the highest share of proton delivery (Fig. 5).

$$Fe^{3+} + 3H_2O \Rightarrow Fe(OH)_3\ (\Downarrow) + 3H^+$$

In the very acidic state, the ferric hydroxide prevails in solution. Therefore, the lakes with pH values less than 3.5 remain with clear water of a dark red-brown colour (Fig. 6).

The overall process of geogenic sulfur acidification may be summarized by the following simplified equation:

$$FeS_2 + 3.75\ O_2 + 3.5\ H_2O \Rightarrow Fe(OH)_3 + 2\ SO_4^{2-} + 4H^+$$

The various methods of neutralization, natural and artificially enhanced, will be discussed later. However, a few remarks may be given about the consequences of raising the pH of the aquatic environment:

- The main change is the decreasing solubility of ferric hydroxide. The water becomes turbid. The colour varies to ochre. The Secchi-depth decreases.
- A co-precipitation occurs, due to which the most heavy metals, bacteria and phosphorus are transferred permanently into bottom sediment.
- At the end of the process the mining lake get its best water quality within the whole succession from the first upcoming groundwater until the final "climax" stage.
- Within the pH-range of the bicarbonate buffer the supply with organic carbon is guaranteed by algae assimilation and, from this time on, phosphorus becomes the limiting factor controlling the primary productivity.

The water chemistry of the mining lakes is governed by three buffering systems: the circumneutral bicarbonate buffer, the acidic aluminium buffer, and the iron buffer. Alkalinization does not change the pH unless the base-binding capacity is saturated.

When this occurs, the pH shifts from one to the next buffering system. The changes are similar to titration curves. In connection with acid rain, the aluminium buffer is dominating. The affected waters prevail in the pH-range 3.6 – 4.2. In mining lakes the iron buffer is absolutely dominant at pH values < 3.8 (Ulrich 1981).

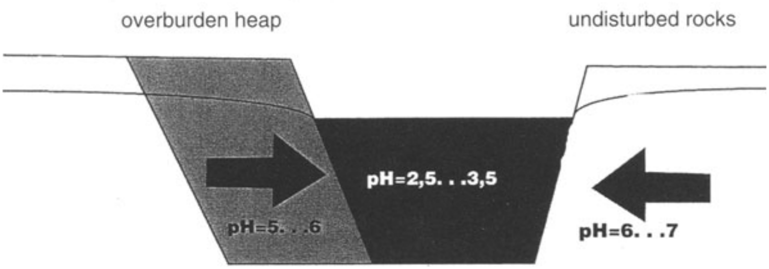


Fig. 5. pH-values in mining lakes and adjacent aquifers (adapted from Reichel and Uhlmann 1995)

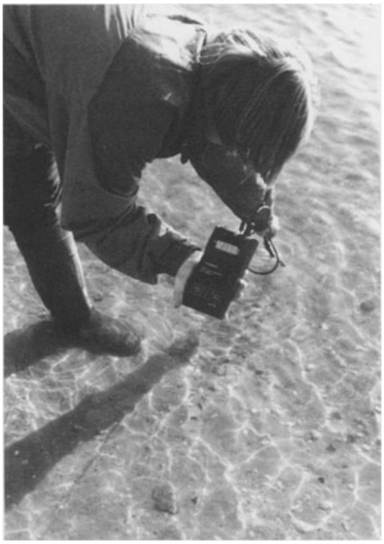


Fig. 6. Acidic groundwaters with dissolved ferric hydroxide, filling the new mining lake Skado, Germany

In the Lusatian browncoal region of Germany, most lakes were found to be at about pH 2 to less than 4 , with others between 6 and 8. One exception, the Felix See, was observed to have a pH of about 4. In this case the concentration of aluminium was ten times higher than that of iron. The conditions in this special case resemble those in lakes influenced by acid rain (Fig. 7).

3.2 Habitat for Plants and Animals

From the immense literature available on acid rain, it seems that hardly any life can be expected at a pH less than 4. Indeed, the youngest geogenically acidified mining lakes with a pH of 2 – 3 are abiotic at first glance.
Nevertheless, such an extreme habitat has been shown to be colonized by specialists, some in great abundance because of the lack of competition.

Organisms able to survive in the extremely acidic environment possess mechanisms for detoxification by ion exchange, by oxidation and flocculation of heavy metals, by excretion of chelates, and by transformation of metals into other dissolved forms with lower toxicity. Some algae respond with dormancy or concentrate toxicants in terminal cells that they later discard (Lüderitz 1988).

Compared to natural lakes, acid mine lakes generally have low primary productivity. Because of the lack of bicarbonate in acidic lakes, algal groups of the *Scenedesmus* photosynthetic type are absent. The first phytoplankton to appear are from the same groups to be found in bog waters: chloromonads, cryptomonads, dinoflagellates, etc.

Important processes occur at the level of the pico- and bacterioplankton. The total algal biomass is low, and this criterion alone would accord with a classification as "oligotrophic" (Nixdorf et al. 1995). This low algal production is unexpected, considering the relatively high phosphorus supply. Obviously factors other than nutrients limit productivity. Moreover, the seepage waters from overburden heaps with a $pH < 2$ are not really abiotic. At least bacteria occur in these waters. The pyrite oxidation itself is described as a chemo-autotrophic microbiological process by some species of *Thiobacillus.*

Besides algal development, heterotrophic degradation is strongly inhibited in the acidic environment. Leaves that have fallen from surrounding trees into the acidic lake remain undegraded for years on the lake bottom. Trees submerged during the filling process persist for decades as undegraded and quasi "acid-preserved." The low respiration rates and low solubility of CO_2 in acidic waters seem to be the reasons for carbon limitation of bioproductivity (Ohle 1981, Schindler 1994). Macrophytes are lacking only at a very early filling stage.

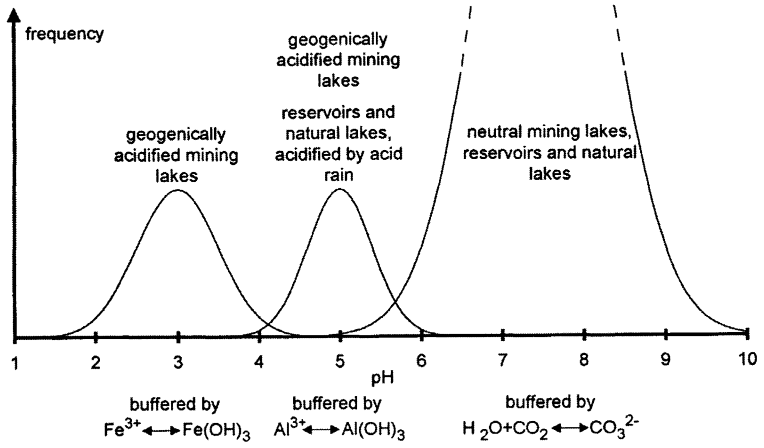


Fig. 7. Generalized frequency distribution of lakes with different acidity in Germany (from Klapper et al. 1996)

Uprising groundwater rich in sulfuric acid, iron and sulphate, a changing shoreline, and an unstable subsurface during the first quick filling phase preclude macrophyte growth for hydrochemical and edaphic reasons. Soon after the hydrological regime has stabilized, however, the typical pioneer plant *Juncus bulbosus* occurs. In this "one species biocenosis" according to biocenotic laws, *J. bulbosus* is very frequent in the littoral zone and also on the lake bottom, if the water is sufficiently clear. Photosynthesis by CO_2-consumption leads to iron flocculation on the stems. Occasionally the ochre precipitation pulls whole plants down to the bottom. This species, which is mainly vegetatively reproducing, sprouts a second time during summer and appears again grass-green in colour. On sunny days the raised pH because of CO_2 assimilation can be seen with naked eyes: in the neighbourhood of the *Juncus* stands iron hydroxide is precipitating (Fig. 8).

Pietsch (1993) distinguished some typical communities characterized by the dominant species besides *Juncus bulbosus* stands: *Potamogeton natans*, *Utricularia minor*, *Sphagnum cuspidatum*, *S. obesum*, *S. inundatum* and the fern *Pilulifera globulifera.* He described a further transition to a stage with neutral water containing bicarbonate and high species diversity. Of the animals, those groups which cannot exist in an acidic environment are those which need calcium carbonate for their skeletons or shells, such as fish, amphibians, snails, mussels and higher crustaceans. During the first filling stages, acid lakes are also without zooplankton. The rotifers (especially *Brachyonus urceolaris*) are inhabiting lakes with $pH < 3$, as does *Chydorus sphaericus. Cyclops* was found at pH 3.5 and higher. *Daphnia* occurred only in circumneutral lakes. Whether acidity excludes them or their absence is caused by the high frequency of invertebrate predators like *Corixa* is not clear (Tittel, pers. comm.).

Fig. 8. Mining lake Roter See near Burgkemnitz, Germany. Iron hydroxide is precipitating due to CO_2-consumption around *Juncus bulbosus*

4 Succession of Water Quality

During the primary filling of new mining lakes and in the first years of their existence, the water quality undergoes considerable change. The rising water level causes a succession from a shallow to a deep lake. The first shallow stage shows no stratification and no oxygen gradients from the surface to the bottom. In the next stage, the first stratification may be critical, because the hypolimnion is extremely small in relation to the epilimnion. Degradable material concentrates in a very small volume and may cause oxygen depletion in the deep water (Fig. 9).

In connection with acidified lakes this oxygen depletion may be desirable. However, unfortunately in this case the autochthonous production of organic matter is usually too low to achieve a depletion of oxygen. With further deepening of the lake, the hypolimnion: epilimnion ratio rises. This stage is wanted in neutral lakes, but unwanted in acidic ones, which need places with anoxic conditions, where microbial neutralisation by desulfurication may occur.

The deepest, wind-protected lakes, as well as the chemically stratified lakes, are susceptible to meromixis, i.e., the deepest water layers are excluded from the usual turnover-phases of the dimictic lakes in spring and autumn. In such cases, the unmixed monimolimnion becomes anaerobic, thus, having preconditions for desulfurication at depth. Nevertheless, meromixis alone is not yet an ecotechnology for microbial neutralization. Only the anaerobic monimolimnion turns to a neutral pH. Due to lack of circulation, the surface-near water layers also remain acidic for decades (e.g., lake Waldsee near Döbern, Germany). Typical sequences of the main characteristics of the water body during the filling with surface water are shown in Fig. 10.

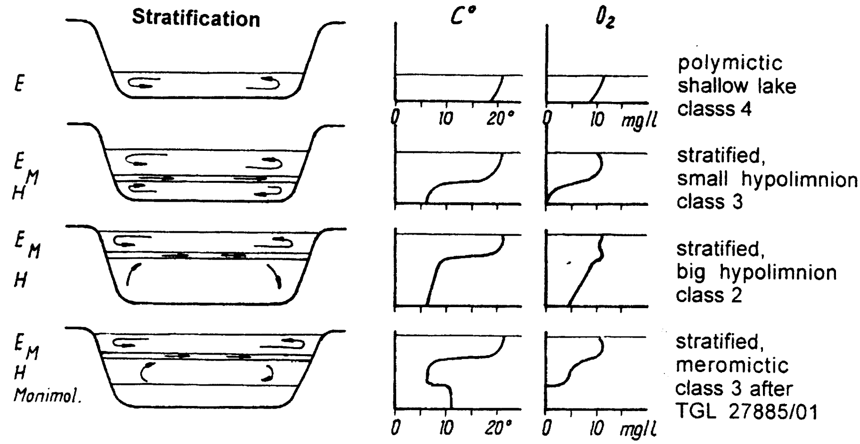


Fig. 9. Change of the stratification along with the filling level of a mining lake (from Klapper 1995)

When mining wells are taken out of operation, a fast rising of groundwater occurs due to the high hydraulic gradient. With the introduction of surface water, the water level in the lake rises faster than the water table of the surrounding groundwater. With the flow-direction from the lake into the underground it is possible to avoid further groundwater entrance and acidification. Towards the completion of filling the lake the introduction of surface water should be finished. Depending on the origin of the groundwater passing through the filled lake, a secondary acidification could then occur. However, there will be no problems with acidic groundwater as long as the acid binding capacity is not used up. If this happens, technologies for neutralization should be considered (see Chapter "Loading of Mining Lakes and Water Quality Control. 1 Acid Mining Lakes").

Similar to natural lakes, the groundwater throughflow is typically accompanied with changes of the water quality because of distinct trapping effects. In the case of lignite mining lakes, the content of, notably, iron, manganese and phosphorus in the entering water decreases due to oxidation and flocculation processes. Organic matter and biomass produced by photosynthesis, nutrients, etc., are incorporated into plankton biomass and transferred to the bottom sediments. The water leaving the mining lake and entering the underground again to become a part of the groundwater, may become anoxic due to the degradation of biologically produced organic matter. The consequences in this case are, for example, denitrification and fixing of sulfidic iron (Fig. 11).

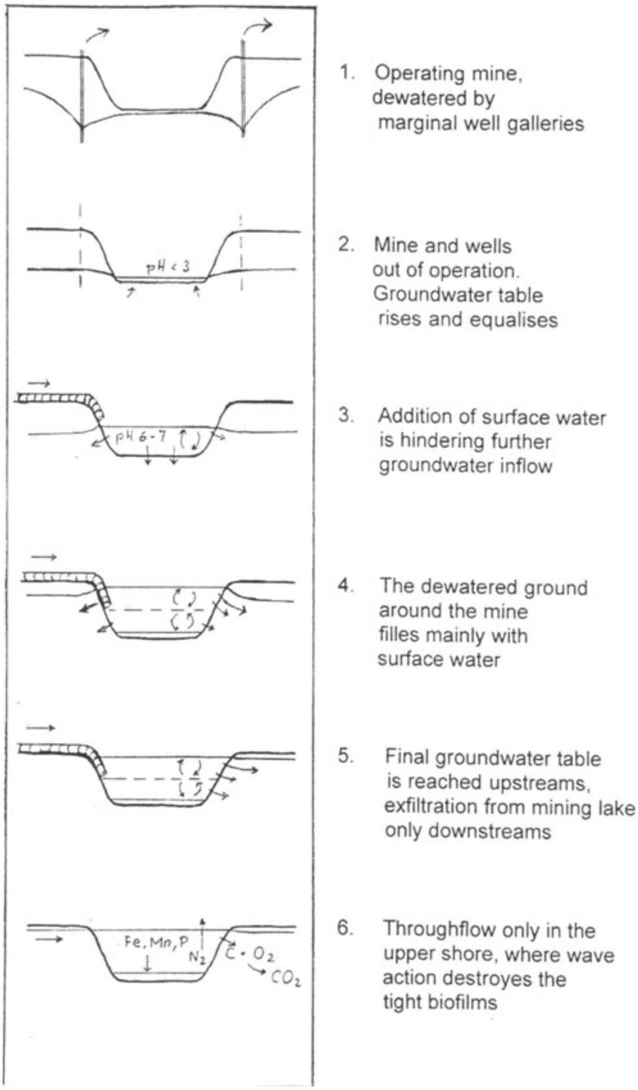


Fig. 10. Filling of a mining hole with surface water; typical sequences (from Klapper and Schultze 1993)

Depending on the nutrient supply of the mining lake in question, the primary production is concentrated in the near-surface layers of nutrient-rich eutrophic lakes or distributed to greater depth in the case of oligotrophic lakes. According to the primary production, the oxygen in the deep water is depleted in eutrophic and nearly saturated in oligotrophic lakes. Very clear waters may be oversaturated at depth, e.g. when *Juncus bulbosus* has overgrown the bottom and performs photosynthesis, as occurs at a depth of 20 m in the mining lake Koschen, Germany.

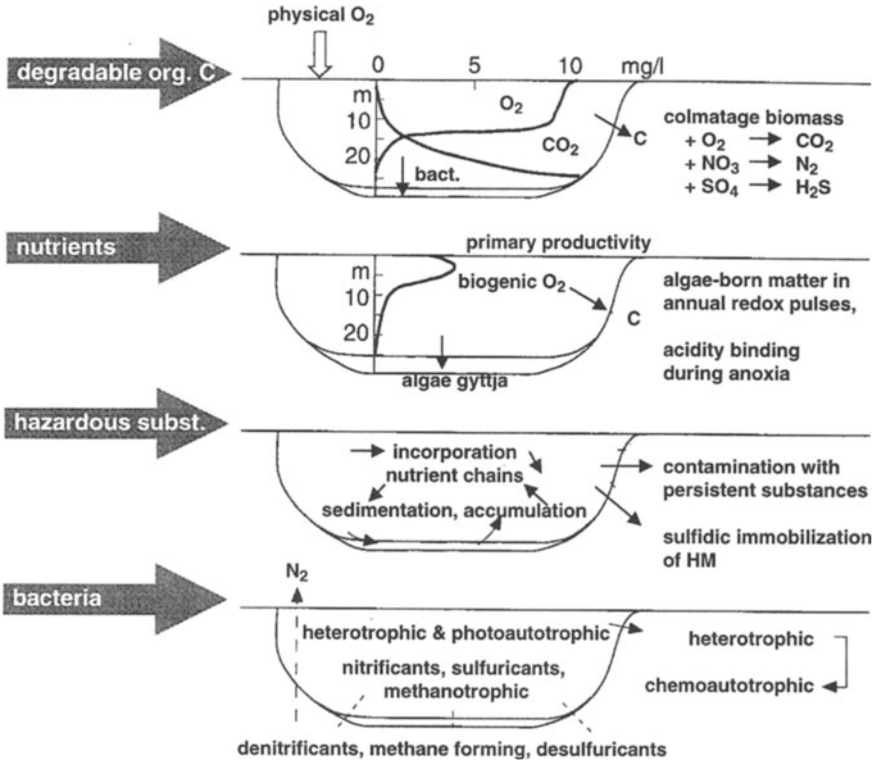


Fig. 11. Different loadings and consequences in mining lakes filled with surface water (from Klapper and Schultze 1993)

Considering contamination with hazardous substances, each case differs from the next. First, the character of the contaminant has to be established: inorganic or organic, degradable or not, solubility, possible introduction in nutrient chains, etc. Groundwater protection deserves high priority, especially against non-degradable contaminants and substances being toxic during bioaccumulation. Nevertheless, the first question should be whether a deposit of hazardous substances exists and what special conditions have to be established for functioning degradation and to allow the restoration of the contamination by in-situ self-purification (see Chapter "Loading of Mining Lakes and Water Quality Control. 3 Contamination"). Bacteria communities in mining lakes differ from those in natural lakes particularly in the first filling stages. Chemolitotrophic iron-bacteria and sulfur-bacteria play the most important role. Bacteria and microalgae hardly compete for the very limited resources of carbon and nutrients. Because of the scarcity of carbon and phosphorus in young mining lakes, such species of algae seem to have selectionary advantages, by which they gain these essential resources by ingestion of bacteria: mixotrophic algae with a special adapted metabolism (Tittel and Zippel, pers. comm.).

The microbial food web in mining lakes (Fig. 11) is the subject of current research in laboratories of several countries. At present it is known that it takes at least decades and sometimes centuries to achieve identical conditions in mining lakes as those prevailing in natural (glacier- or tectonic) lakes. Limnological knowledge, standards and other tools for a good water quality management continue to be developed.

5
Sediments and their Role for the Abatement of Acidification

Sediment profiles and the detailed investigation of the undisturbed layers with the related solid and liquid phases provide an excellent opportunity for reconstructing the history of a lake development. In mining lakes, profiles down to the prelimnic bottom cover the whole succession from the first filling to present day. Therefore, the sediment is correctly called the memory of the lake. With the help of distinct marks, the age of the layers may be determined, so the annual sedimentation rate may be estimated. Such marks include the Cesium peak from the Chernobyl disaster, 1988, or annual white stripes from biogenic calcite precipitation in natural lakes. In some young mining lakes with large amounts of iron precipitated, black and brown stripes allow one to distinguish between the anoxic conditions, due to degradable bioproducts, in summer and oxic conditions in the winter. However, in any one mining lake the sedimentation conditions differ from one area to another. Therefore, the first step is to find correct and representative sampling points. During the first time of groundwater entrance some sediments may be accumulated only in the deepest furrows of the former mine. As long as wind and wave action are able to re-suspend the sedimented matter from the shallow water, the submerged slopes at the lake bottom remain free from sediments, and by the "funnel-effect" the particles concentrate at the deepest localities of the basin (Fig. 12).

Therefore, to estimate the annual sedimenation rate, this variation from no sedimentation at some sites to sediment accumulation at the others has to be considered. The first stage of mining lake formation, i.e. the empty open-cast mine without water, has no sediment at all. The bottom of the hole to be filled consists of sand, gravel, overburden material and residues of non exploited lignite. Important coal areas may be in contact with flooding water, where they were prepared for mining, but not mined due to the new economic conditions.

In Germany, most of the smaller mines were closed immediately after the German unification because of the breakdown of industry and its energy demands. An important question in such cases was the influence of these lignite areas on the water quality of the generating lake and whether it would be necessary to cover the coal with inert soil material in order to avoid occasional water pollution. Fortunately only little effect from the coal on the water column was found and the covering of the coal could be neglected.

The carbon content entering the water as compounds similar to humic substances was much lower than assumed from the red-brown colour of the rain puddles in those areas. Obviously the discoloration originated not from coal extracts, but from dissolved ferric hydroxides at pH < 3. The carbon content in acidic mining lakes has proven to be too small for "normal" functioning of the aquatic ecosystem. With pH < 3 no carbonate, no bicarbonate and only traces of carbon dioxide are present in the sulfuric acid environment. And with low pH-values, low DOC-contents could also be determined. Therefore, it is hypothesized, that carbon is limiting the life starting processes (Klapper and Schultze 1995).

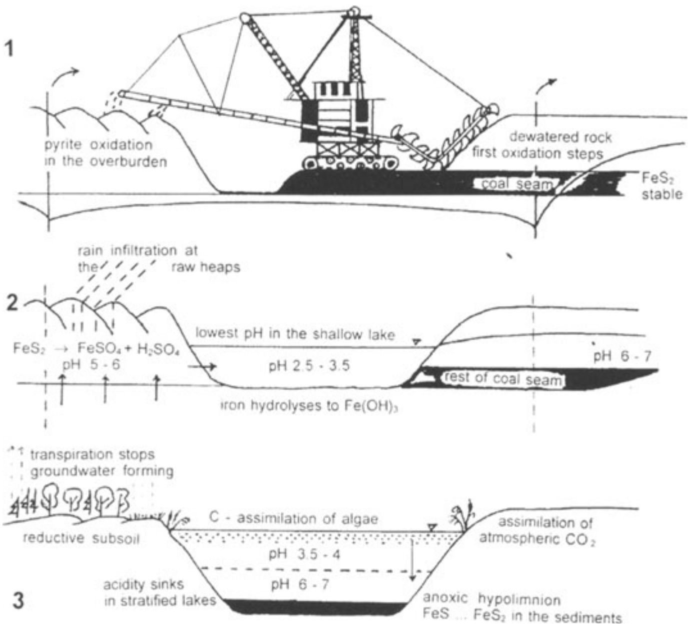


Fig. 12. Development of the lake bottom from acidity source to acidity sink

More important than fulvic substances from lignite, is the organic carbon produced by photosynthesis of plankton algae and the emergent macrophytes. Organic biomass sinking down to the sediments together with iron hydroxide enriches the uppermost sediment layers with degradable matter. Biogeochemical processes in surface sediments such as decomposition of organic matter, reduction of manganese and iron oxides, and bacterial reductions, are the key factors influencing sediment chemistry. Depending on the quality of the organic matter and the lake dynamics, hypolimnetic anoxia can lead to enhanced microbial alkalinity production from anaerobic respiration, raising the pH in the sediments up to neutrality (Wendt-Potthoff and Neu 1998). In particular, iron-reducing bacteria may play an important role in the biogeochemistry of sediments that were influenced by acid mine drainage (Bell and Mills 1987).

The importance of iron-reducing bacteria could be confirmed with help of sediment investigations on mining lake 111 in the Lusatian district (Table 6, Fig. 13, Friese et al. 1998). This lake is 30 to 40 years old, so it can "tell something" about sedimentation processes and diagenesis of the sediments in the past. Mining Lake 111 is used by the Institute of Inland Water Research, Magdeburg, as an experimental lake. The lengths of the sediment cores varied at the deepest parts from 14 to 100 cm. The pre-limnic bottom was easy to be distinguish by the sand and coal particles.

Table 6. Mining Lake 111; main limnological data

Surface area	$10.7 \times 10^4\ m^2$
Volume	$0.5 \times 10^6\ m^3$
Maximum depth	10.2 m
Mean depth	4.6 m
pH (median)	2.6
Sulfate	1310 mg/l
Iron (median)	156 mg/l

Where the lake possesses an anoxic hypolimnion, the sediments are black from reduced iron. On shallower localities the sediments are more light-brown from oxidized iron. Analysis of the cores from the deepest area allows for some general observations (for details see Friese et al. 1998). The redox-potential measured by punch-in electrodes in the field falls from +600 mV on the sediment surface to zero at 2 cm and to –100 mV at 4 cm and lower until 20 cm. The pH measured in the same core was 2.8 at the sediment-water interface, increased until 1 cm to pH 4, prevailed at pH 4 to 2 cm, increased evenly until 8 cm sediment depth to greater than pH 6 and remained at this value until the greatest depth of the core at 20 cm. The surface represents the iron-buffer, 1 – 2 cm the aluminium-buffer and from 8 cm depth the circumneutral bicarbonate-buffer is governing. With the exception of the liquid surface and the sandy bottom the core was sectioned in 1-cm subsamples and analyzed in detail.

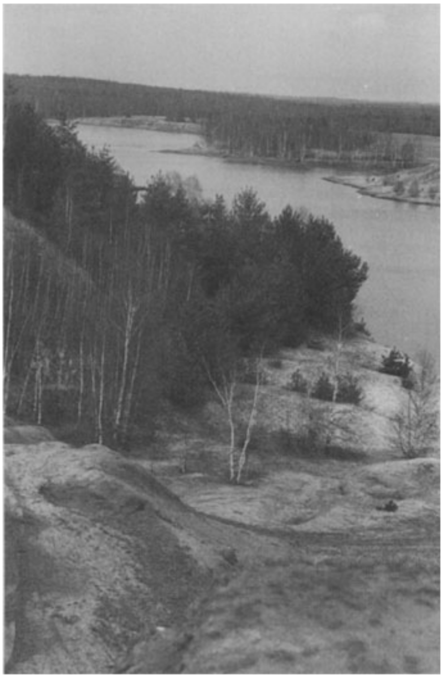


Fig. 13. Research object Mining Lake 111

It could be demonstrated, that during the lifetime of the lake the bioprocesses increased constantly. At the deepest, i.e., from the oldest core section (14 cm), the lowest values were measured in loss of ignition (LOI) 5 %, C_{org} 20 mg/g, TC 20 mg/g, TN 0.5 mg/g, TS 1 mg/g, P 0.2 mg/g. The related values at 2 cm were LOI 22 %, C_{org} 80 mg/g, TC 110 mg/g and TN 7 mg/g dry weight.

The maximum total sulfur was found with TS = 17 mg/g in the 2 – 4 cm section. Phosphorus had two maxima in the 2- and the 6-cm layer with 0.55 mg P per gram dry weight each. The authors assume, that most of the sulfur at 2 – 4 cm depth represents inorganic sulfides, generated during dissimilatory sulfate reduction by anaerobic bacteria. At this depth degradable organic carbon should be present, the E_h was below –100 mV and oxygen penetration can be excluded. Additional support for this hypothesis comes from the high Fe(II)-content and from the fine-grained black material suggesting the presence of ferrous sulfide.

One target of the sediment research is to find techniques for enhancement of the processes of biological binding of acidity, sulfur, iron and other heavy metals in form of sulfides. For oxygen-free conditions, degradable substrates are needed, whether allochthonous introduced or autochtonous produced. However, economical and ecological difficulties are connected with both.

6
End Use/Costs

From an esthetical viewpoint a reclaimed and well functioning post-mining landscape may be more beautiful and pleasant than that before mining. The first heaps from opening the opencast mine dumped on the ground later form forested hills. Deep holes remaining from the excavated coal are later filled with water. They become new lakes in countrysides, where lakes were extremely rare or unknown before. In some regions the mining lakes are occupying large areas of the landscape.

These water bodies are the most characteristic parts of the newly forming lake districts. Their existence should not be understood as a land loss, but as an opportunity for the future. With appropriate management, these lakes will be usable for bathing, diving, fishing etc. Bank filtrated waters are suitable for drinking and processing purposes. The need to make use of the waters depends on the actual demand and the existing infrastructure. The brown-coal industry has had to supply the whole area with long-distance pipe systems for dewatering of the landscape before the mining started. In eastern Germany, the closure of the lignite mining industry with the mines themselves, the coal power plants, briquette factories, smoulderies and chemical coal processing factories has left a landscape of oversupplied infrastructure with respect to traffic, energy, water, food, etc. So, on the one side, the landscape after mining has an excellent infrastructure, which calls for a secondary utilization by new enterprises and business, but, at least temporarily, there is also high unemployment, with only little chance for a quick change. The whole region has been monostructurally oriented on coal and coal processing for decades.

Considering this special situation, it is not surprising that so much interest is directed on the lakes as possible nuclei and attractions for water-oriented tourism including fisheries. Interviews with the inhabitants of the villages around the new emerging lakes have produced similar results everywhere. The people of even the smallest villages want in future the lakes to become “centers” for recreation in order to promote jobs and salaries in related services. However, for economic reasons, only a few such centers should be planned and established. For decision making, the factors of suitability of each lake have to be evaluated.

The development of a mining lake for recreational purposes at first demands several million German marks or U.S. dollars. The return from this starting investment may be realized only from a relatively high frequency of tourists, spending their holidays at the lake, using the local services and spending enough money in the region.

From an economic point of view the lakes in areas under nature protection are far less interesting. With the orientation on “silent recreation” they will attract nature friends and walking tourists with backpacks and binoculars, carrying their own food and usually representing only a very modest business to the local restaurants.

Decision criteria for economic planning can be listed in three groups:

A natural fit of the lake landscape;
B development for recreational purposes; and
C restrictions due to environmental and other impacts.

To assess the suitability of a lake landscapes for recreational purposes, mean conditions may be evaluated as "1", excellent recreational suitability with "2" and absolute insufficiency, e.g. a closed lake, with "0" (Table 7).

Table 7. Factors for evaluating the suitability of lake landscapes for recreational purposes (adapted from Klapper 1995)

A	**"Natural" fit of the landscape and the mining lakes**	
Aa	Size and variability of the lake landscape	1.0 ... 2.0
Ab	Relief forming of the lake landscape	1.0 ... 2.0
Ac	Recreational value of the broader surrounding	0.5 ... 2.0
Ad	Forming and esthetical value of the shore landscape	0.5 ... 2.0
Ae	Geogenic acidity and iron contents	0.1 ... 2.0
Af	Trophic state (polytrophic ...oligotrophic)	0.2 ... 2.0
Ag	Bioclimatic conditions	0.5 ... 1.5
B	**Development of the landscape for recreational purposes**	
Ba	Demand for leisure-, weekend- and holiday-recreation	0.5 ... 2.0
Bb	Development of the local and long-distance traffic, equipment with parking places	0.5 ... 1.5
Bc	Development and mine-technical safety of the shores	0.1 ... 2.0
Bd	Bathing possibilities (not observed or guarded strands and lawns)	0.2 ... 2.0
Be	Restaurants, camping and sporting sites, water and food supply, waste disposal	0.6 ... 2.0
Bf	Possibilities for further activities of water-bound recreation (surfing, diving, sailing and adequate training schools), water travelling, ferries, angling	0.2 ... 2.0
Bg	Cultural and educational offers (museums, concerts, cinemas, discotheques, nature trails)	0.8 ... 1.6
C	**Factors restricting the recreation**	
Ca	Unhygienic conditions, bacteriologically insufficient surface waters for filling	0.2 ... 1.0
Cb	Utilizations adverse to recreation (ash flushing, dumping of hazardous substances)	0.1 ... 1.0
Cc	Turbidity from iron hydroxide, visible scums of oil, tar, hydrophobic coal dust, floating wastes, wood, plastics, bottles etc.	0.1 ... 1.0
Cd	Closing of landslide- endangered shores	0.1 ... 1.0
Ce	Loading by noise and dust from neighboured open pits and power plants	0.2 ... 1.0
Cf	Overloading by too much visitors	0.1 ... 1.0
Cg	Proximity to wasted factories, production ruins, visible traces of landscape destruction	0.1 ... 1.0

The computation of the recreational suitability, R_S, of a distinct landscape with mining lakes can then be performed as follows. The arithmetic means of factors A and B are added and the sum divided by 2 and multiplied with the mean of the factor C. Evaluation of the recreation suitability R_S allows decisions as to which alternative recreational projects are worth subsidising (Table 8). The value of a restoration scheme may also be expressed as an increase in the recreational suitability.

Table 8. Evaluation of recreational suitability

R_S	assessment
0 ... 0.1	not suitable
0.1 ... 0.5	partly suitable
0.5 ... 1.0	suitable
1.0 ... 1.5	well suitable
1.5 ... 1.8	excellently suitable

A capacitive figure, the recreational efficiency R_E, may be introduced. It is given by multiplying R_S by the recreation days R_D, being realized at the mining lake:

$$R_E = R_S * R_D$$

One recreation day may be defined as at least two hours stay of one person with realization of at least one water-oriented activity. To achieve a monetary expression, the R_E has to be multiplied with the well-known costs of one recreation day in an artificially built open-air bathing basin (share of building costs, water treatment and water exchange from public supply, services etc.). This cost may be different in diverse countries, but in every case it is usually much higher than the cost in the new emerging mining lakes, which are large enough that bathing water treatment is not necessary. With this substitutional method only the possibility for bathing is evaluated. The comparably higher value of the new mining lakes results from the potential for diverse water-oriented activities, from the size, the self-purifying large water body, the connection with other lakes and further recreational possibilities in systematically developed landscapes for leisure purposes.

The general question remains, as to whether the mining industry has fulfilled its duty once the lakes are filled and the banks are safe against sliding, or must the lake be usable and the quality of the water suitable, before the lakes may be handed over to the public.

For most cases in Germany, the usability is included into the duties of the mining companies. In the new federal provinces, special enterprises have been established for realizing this. In a countrywide context, this task is not only important for the unemployed people in the mining region itself, but also for the densely populated greater regions of Berlin, Cottbus, Dresden, Leipzig and Halle. The traffic connections generally allow access to the new lake-lands in less than one hour by car or somewhat more by public transportation. The necessary costs have to be invested in the interest of the society – the former mining employees, now waiting for jobs in service enterprises of the tourism industry and also the people from the large cities, wanting to regenerate their working power by active, water-oriented recreation.

One reason for improving the water quality is the fishery. The special conditions in the larger clear water lakes are appropriate for an occupational fishery on the basis of the pelagic food resources. Provided a pH constantly greater than 5.5, or better 6.0, *Coregonus albula* may utilize the zooplakton. Because of the low level of gross bioproductivity in mining lakes, it is useful to produce precious fish species. This way a good monetary yield might be gained with only a small weight of harvest. In larger mining lakes further fish species like pike (*Esox lucius*) and eel (*Anguilla anguilla)* should be inserted, in addition to the introduced and natural fish stock. This constitutes a form of biomanipulation, i.e. the top-down-control of the food chain. Instead of the ichthyoeutrophication to be observed with some cyprinid species a positive influence of the fishery on water quality is possible this way. The best monetary income at such mining lakes with the priority of recreation follows from the sale of licences for sport fishing (Klapper 1998a).

Summarizing this chapter, it can be realized that a usable mining lake has a good potential for a return of the costs that are required to provide safe banks and a sufficient water quality. Moreover, with a diverse selection of mining lakes in the same region, the landscape concerned should develop within a relatively short time as an attraction within the tourist industry. Many people may get new jobs in this service sector of the regional economy.

Lakes established with the only target of being interesting features in nature-near landscapes, having a natural succession without human assistance, may be relatively cheap. However, related to this low expense there will be nearly no financial return or economic benefit to the population. Of course, in the sense of nature protection and for limnological science the value is very high, but it is not acceptable to express natural heritage with its species diversity and natural services in a monetary form.

7
Acid Mining Lakes

7.1
Do you Need to Treat?

Geogenically acidified mining lakes are relatively unique objects of limnology. A few volcanic lakes in Camchatka and Japan and some smaller examples like the sulfur acidic Tonteich Reinbeck near Hamburg, Germany, are described in the limnological literature (Ohle 1981). The largest of such extremely acidic lakes are presently emerging in the Lusatian mining district of Germany.

Without intervention, the lakes would stay acidic for decades or centuries unusable for water-oriented recreation with primary body contact. Also, water sports with secondary body contact, such as canoeing, sailing, etc., would be restricted. Fishing related activities, such as angling and professional fishery, would be absent from these fish-free lakes.

Because many smaller lakes from the older, smaller mines exist, there is no lack of examples for studying all of the problems connected with geogenical sulfur acidification. Such lakes are actually also valuable as part of nature-protected landscapes. In the interests of nature protection some overburden heaps have been kept without recultivation, to become the so-called succession areas, where the vegetation remains very scarce, without trees and with no closed grass cover. Such areas have become places with relatively hotter microclimates within otherwise moderate climatic zones. Hence, these areas are rich in plants adapted to dry conditions, coloured flowers, rare species of insects, and reptiles, etc., usually more common in warmer areas. The groundwater under these heaps remains oxic and acidic. The unrecultivated territory is thus connected with long-term acidification of the lakes in these areas. Eventually, in the future, the acidification will come to a natural end in these areas. This will occur once all oxidized pyrite has been washed out or when the trickling rain water has washed so much of the sulfuric acid to greater depth that a closed vegetation cover will occur and bioproducts and roots will degrade. Further, oxygen in the groundwater will be depleted and the washout of sulfuric acid will stop due to anoxic conditions and reduction of sulfur and iron to form iron sulfides.

Regarding the large lakes emerging from the most recent opencast mines, there is no doubt that only restored, neutral lakes have the quality to be released from the responsibility of the mining enterprise for utilization by the public. In the past, mining engineers had a tendency to consider the mining lakes ready for release after achieving sufficient stability of the banks. However, there was no recreational interest in such useless, large lakes filled with dilute sulfuric acid. The mine enterprises would typically be stuck with ownership of these non-marketable lakes for a long time, and ultimately, this would be more expensive than to satisfying the financial requirements for neutralisation.

From a socio-political viewpoint the necessity to reclaim past surface mining areas is obvious. The people in the mining districts have the right to make decisions about the future of the region, in which they have been working and where mining companies received much money by exploiting the resources and temporarily destroying the landscape. The excellent infrastructure in past mining areas should attract new industries and a beautiful landscape, with lakes, should attract holiday makers. Many jobs in the tourism-sector may be found, provided that the lakes in the region would be usable. With these points in mind, the following chapter gives a brief overview of the necessary steps for abatement and control of acidificaton of acid mine lakes.

7.2 Methods of Curbing Acidity During Lake Formation

Alleviation of acidification should be considered and implemented right from the initial planning stages of mining operations, up until the recultivation of the overburden heaps. If sustainable neutralization is to be obtained, a complex, long-term abatement program must be set up covering a broad range of issues.

In order to minimize the contact of pyritic minerals with oxygen, the temporal and spatial dewatering of the lignite to be mined must be limited. The layers of overburden with the highest pyrite levels should also be dumped in the deepest part of the mine, thus enabling these materials to become submerged as early as possible. The diffusion coefficient for oxygen in water is only 0.0001 of that in air.

The final position of an abandoned mine in the groundwater field influences the acidity input into the mine lake. Groundwater from the undisturbed rock is mostly neutral, whereas that from the overburden heaps is acidic as a result of the oxidation of all the sulfidic ores during the mining process. Therefore, the end-position of an abandoned mine in the greater groundwater field should preferably be downstream of the undisturbed rocks and upstream of the groundwater forming in the overburden heaps.

The important role of the filling water has been already described in Section 2. Mining lakes, extending over great distances in the direction of groundwater flow may act like discharging or recharging groundwater wells. The lakes are horizontal levels within the slope of the underground water table. A deeper lake level draws water from surrounding aquifers upstream, while lower aquifer levels cause surface water to infiltrate down through the ground beneath the lake. In order to avoid intensive flow and mass transport of dissolved matter, such long-shaped lakes should be subdivided, thereby decreasing the hydraulic gradient, as shown in Fig. 14.

Revegetation of the acidic heaps can be boosted by chemical treatment with alkalinity-delivering materials such as lime or ash. In eastern Germany, with low precipitation of about 500 mm/year, the establishment of mixed forests, with the associated high evapotranspiration rates, reduces groundwater infiltration to nearly zero. The soil and humus cover of the forest decreases unwanted oxygen penetration to the subsoil (#1 in Fig. 14). Similar findings are to be observed with permanent grassland and organic fertilizers (#2 in Fig. 14). Wetlands and fishponds can be reestablished in the lowlands along the rivers and creeks. These were typical of the Lusatian landscape in Germany prior lignite mining. The wet covers prevented the aeration of the ground (#3 in Fig. 14). The application of detergents, which kill the bacteria responsible for acid formation, is appropriate for smaller heaps rich in sulfidic ores. Although toxic to *Thiobacillus,* these materials provide a degradable and oxygen-consuming substrate for the other heterotrophic microorganisms (Kleinmann et al. 1981; Rastogi 1996; #4 in Fig. 14).

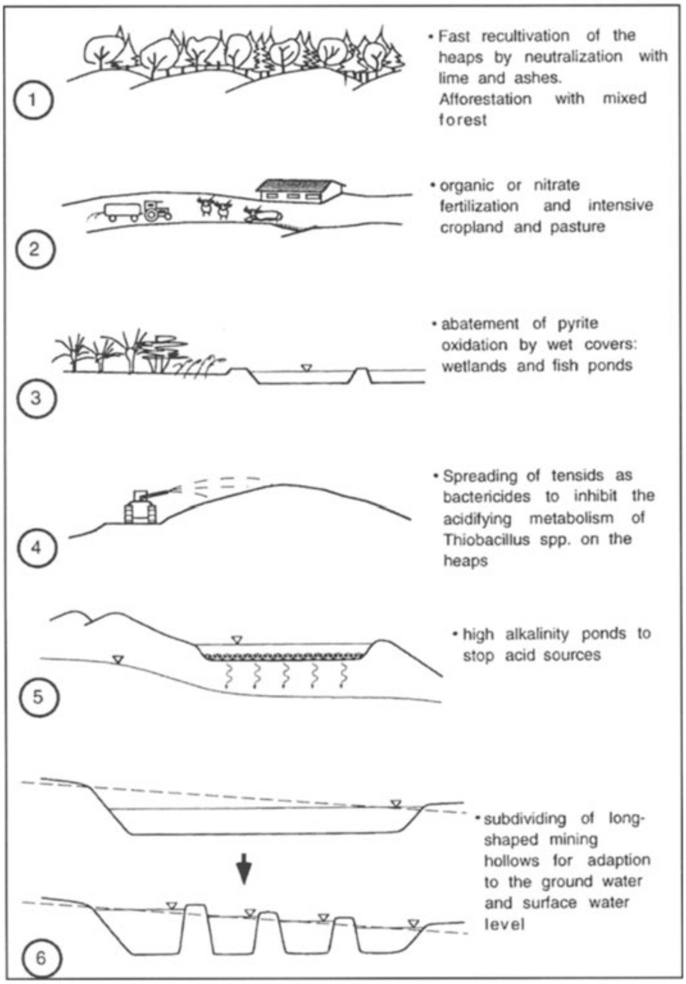


Fig. 14. Abatement of acidification by measures in the drainage basin (from Klapper and Schultze 1997)

High-alkalinity ponds are recommended for neutralizing ground-water outlets to mining lakes. With limestone on the bottom, such ponds promote infiltration of alkalilnity into the acidic ground (#5 in Fig. 14).

7.3 In-situ Neutralization of Mining Lakes

The natural geogenical processes causing acidfication are summarized in Fig. 15. The left side corresponds to conditions in a lake, filled only with groundwater and being too shallow to become stratified by temperature-driven density gradients. With oxygen present in nearly all compartments of the lake system, including bottom sediments, the acidity will stay for decades. On the other hand, in a stratified lake (right side) there are anoxic parts in the sediments, in the hypolimnion and, in cases when the lake is meromictic, in the monimolimnion. Carbon-limitation may be overcome with external carbon imports or by bioproduction. The emergent macrophytes are independent with respect to carbon-supply, because they receive CO_2 from the inexhaustible resource in the atmosphere. At the same time they produce degradable organic material by photosynthesis. The sediments of the reed belt, with its rhizomes, are areas of sulfate reduction, with the visible black colour of the rotten plants, sometimes interspersed with golden crystals of pyrite. In addition, leaf-litter from trees near the shore produces microhabitats for sulfate-reducing bacteria.

Fig. 16 illustrates a number of ecotechnological in-lake approaches for neutralization. The ideas originate from observation, the literature, experience gained while tackling similar problems (e.g., with the aim of controlling nitrate), and from laboratory experiments. Many relatively small and shallow lakes have remained acidic for decades. Other lakes with stable stratification were neutralized within few years by internal mechanisms. Ecotechnologies functioning on the basis of microbial sulfate reduction require the absence of oxygen and nitrate, and the availability of a carbon source for sulfate respiration (Fig. 15). Both stratification and mixing in a lake depend on the length of free wind action or the wave fetch. Stratification is a desired condition for acid mitigation.

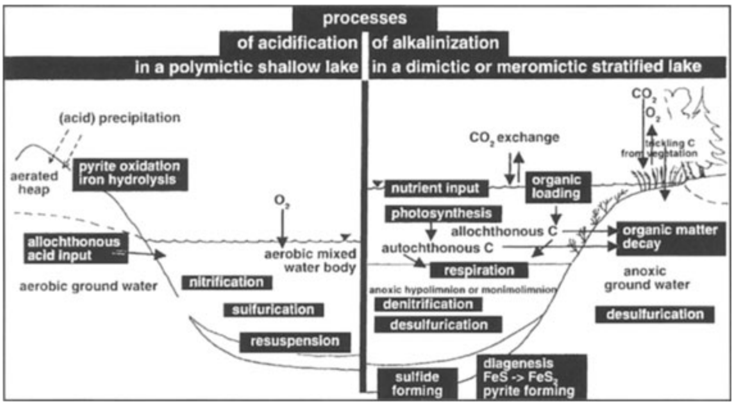


Fig. 15. Processes affecting acidity in shallow and in stratified water bodies (from Klapper et al. 1998)

To show how efficient stratified systems can be, Lake Fuchskuhle, a shallow moor lake in eastern Germany, was divided into four limnocorrals with help of plastic sheeting. The corrals became stratified with anoxic deep water and sediments. As a result, the pH changed to nearly neutral while nutrients and bioproductivity increased (Babenzien 1996).

Possible tools to induce such stratification in mining lakes include oil barriers, floating reeds and submerged foils positioned from the bottom into the open water like a fishing net. The provision of wind protection by the shore is only effective where lake areas are small (#1 in Fig. 16).

The main way of attaining a neutral mining lake in the Lusatian region of Germany is to first rapidly flood the pits with surface water. Although installation of the necessary pipelines or ducts is expensive, this approach has the additional benefit of providing shore stability (Luckner et al. 1995). Running surface waters contain neutralizing and buffering bicarbonate, nutrients, and dissolved and particulate organic matter, all of which are ingredients for the abatement of acidification. In order to avoid excessive nutrient input, towards the end of the flooding process the river should function only as a bypass of the lake. To satisfy any neutralization requirements, no more than the necessary amount of surface water should be used (#2 in Fig. 16).

The addition of phosphorus to a rain-acidified, soft water, upland lake in England led to neutralization by the above-described mechanisms. A total of 5.9 m^3 of a phosphate solution brought about the effect of 34 tonnes of calcium carbonate (Davison et al. 1995, George and Davison 1998).

For restoration of the pelagic food web in acidified and limed lakes, a gentle fertilization may be useful (Bell et al. 1993; Olofsson et al. 1988; #3 in Fig. 16). In very acidic mining lakes, fertilization with treated sewage containing not only nutrients but also organic carbon appears to be successful. One good example of neutralization by sewage is the case of Laubusch mining lake in Germany. During stagnation periods sulfur and iron are transported into the black bottom sediments, fixing the acidity. With pH values of 3 – 4 in the epilimnion and 6 – 7 in the hypolimnion, a good stock of fish has developed in this lake (Klapper and Schultze 1995). In lakes, neutralized by flushing with surface waters, but endangered under low water conditions by entrance of acid groundwater and reacidification, a desirable eutrophication may be achieved with the help of trout breeding in net containers. This will help to stabilize the neutral conditions with generating anoxic sediments and deep waters. Desired oxygen consumption results from uneaten food and fish feces. This kind of artificial eutrophication is not connected with pipelines or other construction and may be licensed temporarily, so that it may be finished, if necessary, relatively soon. For the professional fisheries this kind of fish production is profitable and would stabilize the income in those cases, where the *Coregonus* (white fish) harvest is too low for a sufficient income. This has been realized at the mining lake Senftenberger See in Germany (Rümmler, pers. comm 1998).

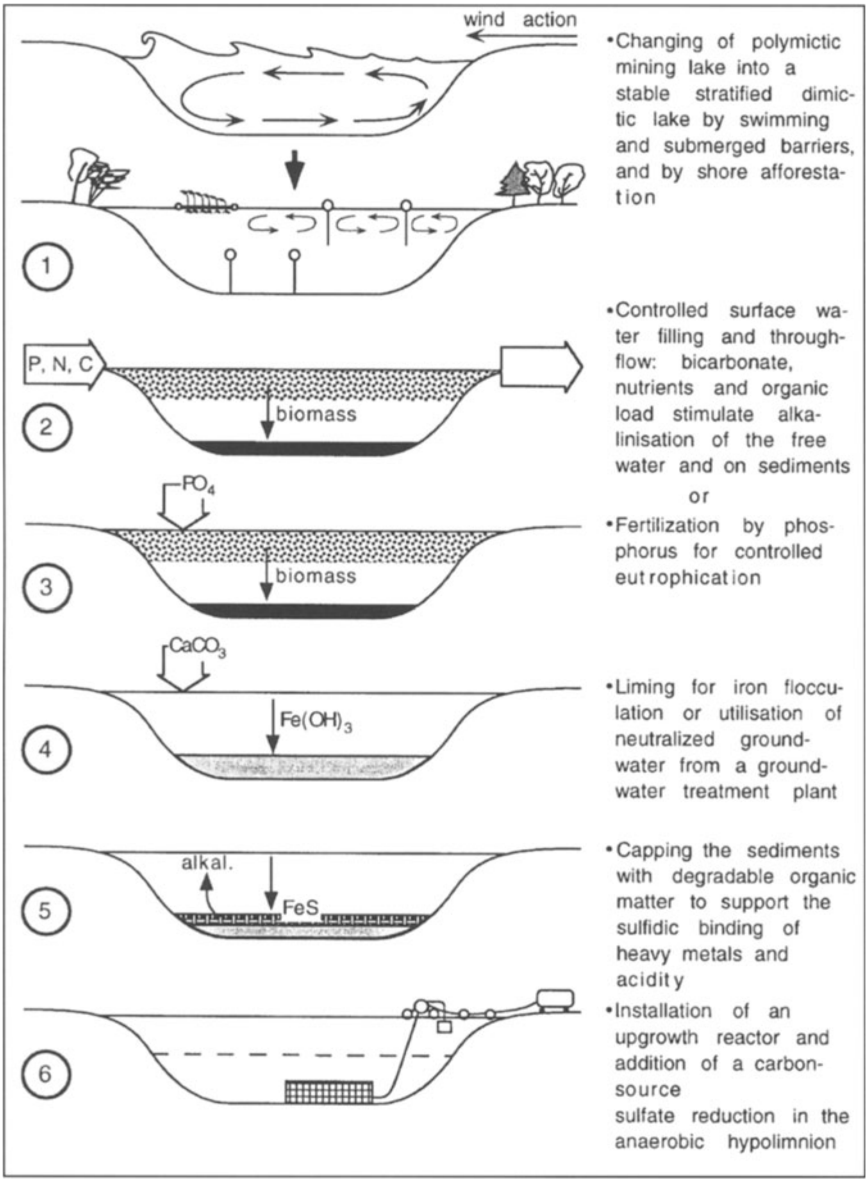


Fig. 16. Abatement of acidification by in-situ technologies (from Klapper and Schultze 1997)

Liming has been successfully applied in Canada, the USA and Sweden to neutralize rain-acidified lakes. In Sweden, about 5000 surface waters have been neutralized since 1988 under a government program (Olem 1991). In most cases calcium carbonate is used, providing alkalinity and inorganic carbon. The soft-water bodies are quite different from hard-water mining lakes. The latter are strongly buffered by iron at a far lower pH and the alkalinity demand is about tenfold higher for neutralization. In the Lusatian region of Germany several groundwater treatment plants exist for the neutralization of effluents. They may now be used to produce limed and cleaned water to fill newly emerging lakes. However, this ex-situ treatment is expensive (#4 in Fig. 16), consequently restoration research focuses on natural process of alkalinization by desulfurication.

The addition of organic matter may provide a way of enhancing the sulfide-forming properties of the sediments. Promising experiments are currently being performed by Fyson and Nixdorf (1996, pers. comm.) with potatoe chips as the carbon source, as well as by Frömmichen (1998, pers. comm.) with the addition of organic loaded saturation chalk from sugar factories or liquid organic substrates. Another proposal has been to dredge the sludge from eutrophic lakes and to spread such lake sediments on the bottom of acidic mining lakes. This method of restoration is designed to counter eutrophication in the case of natural lakes and acidity in mining lakes (Nixdorf et al. 1997; #5 in Fig. 16).

Another example of an effective anaerobic ecotechnology has been developed for heterotrophic nitrate dissimilation in Zeulenroda Reservoir, Thuringia, Germany. A steel cage measuring 20-m x 60 m x 1.5-m, filled with 13000 bales of straw, and equipped with distribution pipes, was positioned on the hypolimnic bottom near the dam. Nitrate-rich surface water was pumped through the straw reactor together with fatty acids to provide a carbon source. The dissolved oxygen was quantitatively released, after which the nitrate oxygen was utilized. Nitrogen escaped in molecular form. If methanol is used to represent the hydrogen donor, the process can be expressed by the following overall equation:

$$6\,NO_3 + 6\,CH_3OH \Rightarrow 3\,N_2\uparrow + 6\,CO_2 + 12\,H_2O^-$$

This technique enabled the hypolimnion to become anaerobic and nitrate-free within eight weeks. The water was reaerated along a stretch of 5 km of turbulent flow between Zeulenroda and a terminal reservoir and proved to be a suitable source of raw water for drinking water supply (Fichtner 1983; Klapper 1991; #6 in Fig. 16).

7.4
Ex-situ Treatment of Mining Lakes

A pilot scale, ex-situ bacteriological sulfate reduction scheme is underway at the mining lake Kahnsdorf south of Leipzig, Germany (Glombitza and Madai 1996). The closed anaerobic biofilm-reactor is supplied with lake water and methanol is used as a carbon source. Methanol is needed at a ratio or around

1:1 with reduced sulfate. Vibrionic bacteria, immobilized on up-growth carrier material, are most efficient. Methanol is consumed totally. A drawback is the relatively low capacity for the large volume of the lake (see also Brettschneider and Pöpel 1992).

A further approach is based on an electrolytic hydrogen generation, with reduction of oxygen and precipitation of heavy metals. By this approach the pH rises by proton consumption. The energy demand is preliminary estimated to be 0.5 – 1.2 kWh/m^3 lake water (Friedrich 1996). Application of this technology on a technical scale has yet to be established.

Several established ex-situ technologies for the recovery of acidic waters are summarized in Fig. 17. Alkalinity production or acidity binding is best accomplished in fully or partly anaerobic systems, while the precipitation of unwanted heavy metals is best achieved in aerobic macrophyte systems after the pH has risen to neutrality. Many proposals comprise combinations of anaerobic with aerobic steps, sometimes with limestone as an inherent constituent of the various stages. For example, anoxic limestone drains are widely used in the U.S. to satisfy the alkalinity requirement of acidic and metal-containing mine effluents. Anoxic operation is necessary to avoid clogging by the precipitation of metal hydroxides. A trench is dug and lined with plastic sheeting before being filled with limestone. The ends of the plastic sheeting are wrapped over the limestone and covered with soil. The inlet and outlet are protected against aeration by traps such as u-bend pipes (Hedin and Watzlaf 1994, #1 in Fig. 17). This approach may also be suitable for the lignite-mining regions of Germany. As soon as a self-sustaining water balance has been re-established, the neutralizing service ecosystems (i.e., anoxic limestone drains) should be set up at lake inlets or along connecting trenches between two mining lakes.

Several other technologies have potential application to the East German lignite-mining regions. For example, in California, deep, narrow trenches filled with bales of straw serve as anoxic denitrification facilities (Brown 1971; Sword 1971; Jones 1974). When denitrification is complete desulfurization takes place in the same system (#3 in Fig. 17).

At the Wheal Jane Pilot Plant in the UK, closed plastic-coated upgrowth reactors are filled with degradable or inert up-growth materials and, with the addition of substrate, support microbial desulfurization. Sulfides remain inside the reactor, but the effluent has to be re-aerated (Taberham pers. comm.; Lamb et al. 1998; see #4 in Fig. 17).

Successive alkalinity-producing systems can also be used. These consist of infiltration ponds with a drained layer of limestone covered by an organic layer, put in place to consume the dissolved oxygen. However, problems with throughput can arise from clogging of the bottom by microbial biofilms (Kepler and McCleary 1994; Nawroth et al. 1994; #4 in Fig. 17).

Anoxic biofilm chambers, which are deep small ponds supplied with oxygen-consuming organic matter, operate without infiltration.

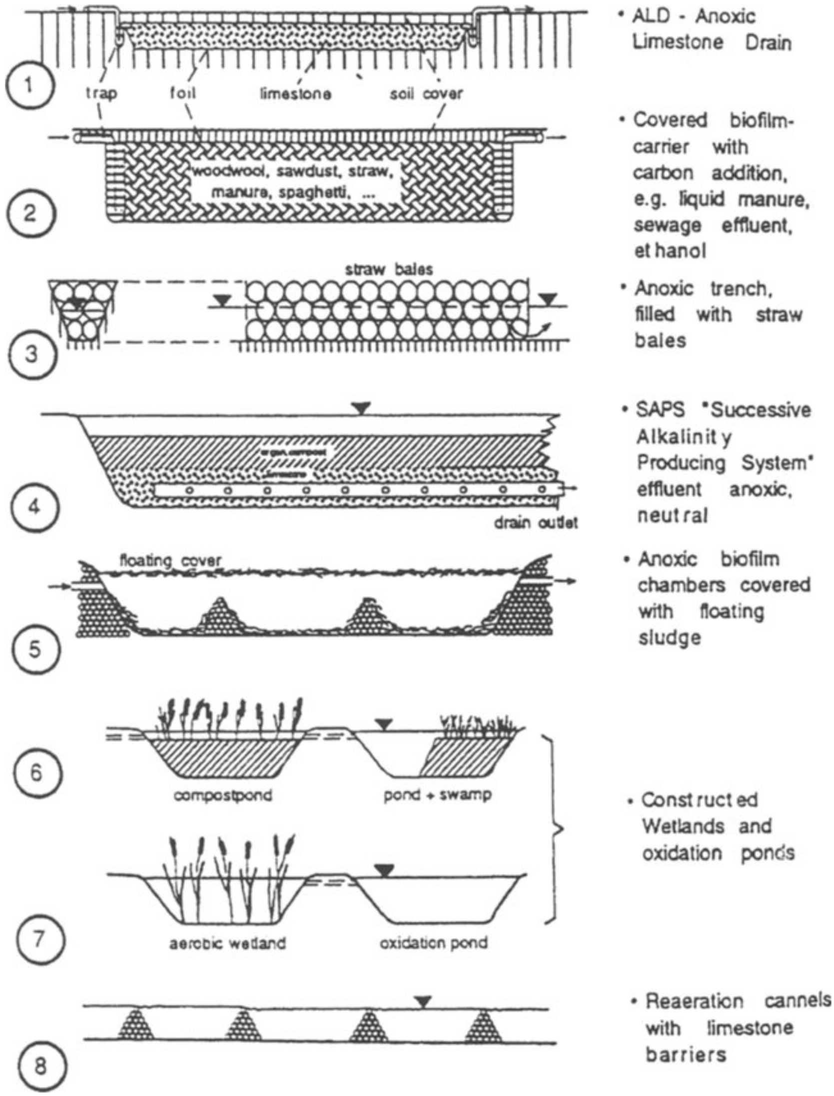


Fig. 17. "Service ecosystems" for neutralisation of acidic effluents (from Klapper and Schultze 1997)

Comparable to inefficient sludge digesters, the floating cover in this case is an essential part of the technology. Silage fodder has proven to be the most suitable organic material (Kalin pers. comm.; Philipps and Bender 1998). The mining lake Haselbach 1, south of Leipzig, Germany, has by chance developed in this way. The 6-ha large, 10-m deep lake is completely overgrown by Cattails *(Typha angustifolia, T. latifolia)*. Its waters have been used in a briquette factory and as a settling basin for cleaning waters of an industrial fodder drying facility. There were sufficient hydrophobic floating coal particles and heterotrophic biofilms for the cattails seed to sprout and to overgrow the whole mining lake within two years. Now the lake is a nature protected area and it is strongly forbidden to walk on the dangerous floating plant cover. At present, artificially grown reeds on special mats made from coconut fiber are available for starting such floating macrophyte covers. Under the floating cover the water is black, anoxic and neutral, but hidden from sight. At first glance the reed looks like a pleasant wetland (#5 in Fig. 17).

Constructed wetlands, in various configurations, and oxidation ponds serve the aerobic polishing of anaerobic neutralized waters (#7 in Fig. 17). A few approaches include anoxic sections (#6 in Fig. 17). Metal hydroxides are transferred into the permanent bottom sediments (Hedin 1989). For successive alkalinity delivery, watercourses may be equipped with limestone beds. Reaeration can be implemented with the help of limestone overflow barriers (Dietz et al. 1994; #8 in Fig. 17).

Summarizing this section on acidification, it appears that the abatement of geogenically sulfur acidification includes measures to combat pyrite oxidation, steps to decrease groundwater and acidity transport, as well as in-situ and ex-situ neutralization processes. Chemical neutralization is often impracticable because of the large amounts of alkalies and the costs of the treatment. Large mining basins should primarily be flooded with surface water containing bicarbonate. A temporarily higher trophic level in the lakes must be tolerated. The most promising alternative for chemical neutralisation is the encouragement of microbial processes of anaerobic acid binding by desulfurization. Aerobic treatment with macrophyte systems, such as in artificially constructed wetlands, is suitable for completing water treatment via the flocculation of the heavy metals contained as hydroxides. The research findings discussed above can in principle be applied to the mining of nearly all pyrite-containing rock such as hard coal, quarz and slate, as well as sulfidic ores (especially uranium). More detailed information about the basics of geogenic sulfur acidification, limnology and management is given in the book "Acidic Mining Lakes" by Geller et al. (1998).

8 Eutrophication

8.1 When to Treat?

Control of eutrophication is high priority in neutral mining lakes, in order to achieve a good water quality. However, definition of "good water quality" depends on the final use of the lake. As outlined before, water quality is usually assessed from the standpoint of utilization by humans. High demanding uses, e.g., for bathing or drinking purposes, need clear water with a low bio-productivity, i.e., low content of plankton algae. Nevertheless, in the case of shallow mining lakes in protected natural landscapes, the aim of which is high species diversity, eutrophication is no drawback and control of eutrophication should not be a necessary target of management. Consideration of acidic lakes where a distinct eutrophication may contribute to the formation of anoxic parts in the lake for generating microbial binding of acidity, has been described in the above chapter.

8.2 Prophylactic and Dietary Measures Against Eutrophication During Lake Formation

Water quality management of neutral mining lakes should be performed with the help of the knowledge and instruments that have been developed by the limnological research community for neutral lakes and reservoirs. However, in connection with mining lakes there are often many further opportunities to utilize the benefits of the generated water quality. In Section 1, the hydrographic principles required for the formation of clear water lakes were summarized: great depth, steep banks, large hypolimnia, small drainage basin etc. Unfortunately, the depth is often decreased by dumping of overburden layers from other mines or flushing the ash from power plants into the empty mine, instead of creating heaps or ash ponds above the surface of the old land.

Mining geologists responsible for the safety of the banks and shores of mining lakes, work at great expense to generate shallow slopes with a low probability of sliding. From a limnological viewpoint, flattening of the shore decreases the volume of deep water, increases the area of lake bottom in the epilimnion, decreases the mean and maximum depth, etc. Nearly all morphometrical factors influencing the trophic state are worsened. This conflict between geo- and hydro-scientists has to be solved as a compromise. Slopes have to be reduced where the safety is endangered, but not more than necessary. There are also possibilities to hinder people from entering the bank-side by planting thorny brambles, or similar shrubs and trees. Some steep slopes should remain for ecological reasons. At stretches undisturbed by mining, where rock layers have good stability, vertical shores are desirable as they provide valuable habitats for rare animals.

As discussed above, water quality is already influenced during the formation of an opencast mine. When the water has completely filled the hole, the highest priority has to be given to the control of the main cause of eutrophication, i.e., to the nutrient input.

Phosphorus is the most important growth-limiting factor in neutral mining lakes. Because of the special conditions by which phosphorus is precipitated by iron-rich groundwater inflows, and due to P-binding on the mineral bottom of recent mining lakes (and given a relatively high nitrogen supply), *a decrease of phosphorus concentration in the lake water is the key for controlling eutrophication and improving the water quality*. The spectrum of possible measures to control eutrophication will be discussed with help of a simple illustration, developed for neutral lakes (Fig. 18).

Items #1 and #2 in Fig. 18 are interesting in the case of mining lakes. A sewage-free drainage basin may be best realized by sewage diversion to more distant sewage treatment plants outside of the drainage basin. This concept of greater treatment plants includes also tertiary purification by chemical phosphorus precipitation or by biological P- and N-elimination by the anaerobic/aerobic change within the activated sludge process. For example, in Germany, nutrient elimination is prescribed for all larger treatment plants serving more than 20,000 inhabitants or equivalent.

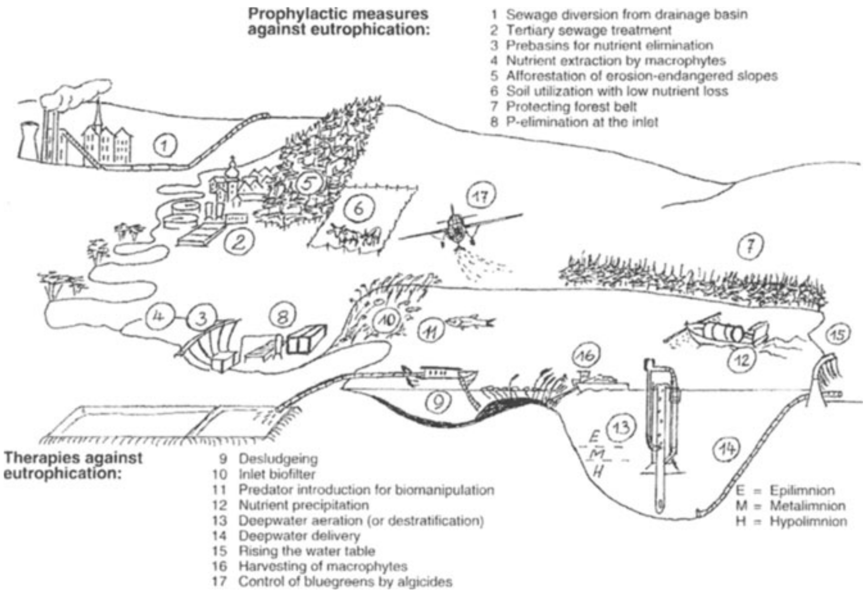


Fig. 18. Methods to protect and restore lakes against eutrophication (adapted from Klapper 1980)

The utilization of storage reservoirs for nutrient elimination (#3 in Fig. 18) has been discussed in Section 2, highlighted by the case of the Mulde Reservoir. Techniques for harvesting nutrients by macrophytes are relatively modest and are restricted to the growing period (#4 in Fig. 18). Protected, shallow underwater parts in the inlet area have to be prepared for this technique. When the final water level is reached and the shore and bottom are sufficiently stable, it is possible to develop *Typha*- and *Phragmites*- stands by systematic planting. The macrophytes are the up-growth carrier for the periphyton, consisting of biofilms with autotrophic and heterotrophic microorganisms. Macrophytes and periphyton form biofilters or the so-called bioplateaus (Oksijuk and Stolberg 1986).

Reforestation is part of the overall recultivation of the mining territory and in particular the heaps (#5 in Fig. 18). In the context of the mining lakes, the importance of reforestation is the associated high rate of evapotranspiration, which curbs the rate of groundwater infiltration. Forestation of reclaimed mining areas is discussed in Chapter "Alternatives for the Reclamation of Surface Mined Lands. 3.3 Forestry".

Reducing nutrient export from agricultural land uses is one means of tackling the dangers of eutrophication in mining lakes (#6 in Fig. 18). To achieve this, well-known principles from soil science have to be followed to establish stable soil ecosystems. A good, crumbly structure and sorption ability will emerge, when soil is well supplied with organics, settled by bacteria, fungi, collemboles, worms, etc., and carries a vegetation cover the whole year.

Protecting wood strips are shown in Fig. 18 (#7) as coniferous forests. These have been recommended for drinking water reservoirs, to avoid fallen leaves loading the water body. However, use of coniferous trees alone should be restricted to the edge of the wood along the shore. It is recommended that the rest of the forest should be cultivated with mixed deciduous and coniferous forests. With leaf-mould, such forest produces a healthy soil fermentation with good sorption ability. On the contrary, pure needle deposition produces a non-degrading raw humus with a poor sorption capacity for key nutrients.

Phosphorus elimination at a lake inlet (#8 in Fig. 18) has been used in research and planning stages, to treat unsuitable mine-filling water from loaded rivers. Since such treatment plants are only used at one location for a few years, they should be designed with:

- robust and simple technology,
- a small percentage of non-transportable concrete buildings,
- a high percentage of prefabricated units, of variable applications based on a modular principle,
- low maintenance and operation expenses,
- simple deposition of flocculation or adsorption sludge,
- parts that are easy to dismantle and reuse at the next site.

No technical scale treatment plants for P-elimination at mining lakes have been built in Germany to date. The treatment of the inflow has been performed by using existing water bodies as pre-basins as described in the TGL 27885/02 (1983) standard. For filling the mining lake Cospuden, south of Leipzig, Germany, a slow sand filtration had been investigated on a pilot scale. The actual solution with untreated groundwater from the active opencast mine Profen has been described in Section 2.

8.3
In-lake Measures Against Eutrophication

Desludging is only a solution to eutrophication in very old mining lakes (#9 in Fig. 18). Even several decades after lake formation, the remaining mining structures can disturb all types of suction dredging. Only the furrows fill with soft sediments while elevated areas of the lake bottom are free from sediments.

The potential to eliminate nutrients with the help of macrophytes has been discussed (#10 in Fig. 18). Only a small share of the nutrient budget will be incorporated in the biomass and may be harvested by reed cutting. The intake is performed mainly in the early summer during the growth period. In the cold season the delivery of matter from degrading plants predominates.

Predator fish may be introduced as a top-down biomanipulation of the nutrient pyramid. With a subsequent reduction of prey fishes, the zooplankton have a better chance to survive and, therefore, to graze on phytoplankton. With less phytoplankton, the water becomes clear and more usable (#11 in Fig. 18). There are also some conflicts with fishery management on the mining lakes. One of the most important fish species to make use of the relatively scarce nutrient resources of the free water in the pelagic zone is *Coregonus albula*. Feeding mainly on zooplankton, the introduction of coregonids has a negative effect with respect to the control of eutrophication (Section 6).

Nutrient precipitation within the water body (#12 in Fig. 18) may be an appropriate option, if blue-green algae predominate due to a high phosphorus contents. Water blooms interfere with bathing activities. Dead algae have a stinking odour and cause the development of germs. Consequently bathing has to be prohibited.

At a 100-ha mining lake generated by gravel excavation near Magdeburg, Germany, a precipitation has been performed. A 490-t solution of aluminium sulphate was applied, corresponding to 5.7 g Al^{3+} per m^3 of lake water. Since this application the phosphorus concentration remains at a low level, the visibility of the Secchi disc is high (about 5 m during the summer time), and water blooms no longer occur. The surprisingly long lasting effect seems to be caused by sediment capping with aluminium hydroxide and aluminium phosphate, hindering the re-dissolution of the sediment phosphorus also under anoxic conditions (Klapper 1994). Before applying such an expensive chemotherapy to lakes from lignite mining, all further possibilities should be considered. Cheaper materials with P-binding properties may be found in the vicinity, such as ashes, clay overburden materials, iron-rich groundwater, etc.

Deep water aeration and destratification (#13 in Fig. 18) may be applied against eutrophication, if there is evidence of a better phosphorus binding due to a higher redox potential at the water-sediment interface. This effect has been overestimated in the past. Nevertheless, aeration or circulation of the deep water at least provides the benefit of a larger habitat area for fishes and their food supply. A combination of deep water aeration and the addition of iron-rich well waters has improved the water quality in the mining lake Kayna-South, Germany (Scharf 1998). The delivery of deep water (#14 in Fig. 18) is only an option for lakes with high through-flow. In a stratified lake, during stagnant periods, a vertical gradient is observed with high nutrient concentrations and low oxygen content in the deepest parts of the lake. This causes a trap effect and natural eutrophication. Similar to reservoirs with bottom outlets, deep water delivery in both natural lakes and mining lakes, with help of the Olszewski-tube, increases the export of nutrients and the export of oxygen deficit. The nutrient load decreases and the oxygen balance improves. If deep-water delivery is planned in the case of mining lakes, the necessary tubes may be easily installed in the empty basin before filling the lake.

The water level in the lake may be elevated with the aim of improving trophic conditions associated with a greater depth and volume (#15 in Fig. 18). The final water surface level of the mining lake should be at least in equilibrium with the adjacent groundwater table. To artificially keep down the lake level, e.g., to protect low lying buildings erected during the time of mining operation, should be avoided, if possible. Keeping a low lake level would be inconsistent with the principle of sustainability, as well as with the target of a good water quality with a low trophic level. At relatively shallow, older mining lakes, the harvesting of macrophytes is sometimes the only possible way to allow continued recreational and fisheries use (#16 in Fig. 18). During intensive macrophyte growth most of the phosphorus is incorporated in the plant biomass and may be eliminated with the harvested weed (Sampl 1979).

Another option may be to leave the plants as they are and to observe the succession towards a wetland. Distinct silting or landing stages are rare in "cultivated" country and may be interesting objects of nature protection, too.

The application of copper sulphate for eliminating blue-green algae should be taken into consideration only in extreme situations when it is necessary to guarantee the drinking water supply (#17 in Fig. 18). In the warmer countries of North and South America copper application at drinking water reservoirs is quite common, even though, because of the fish toxicity, only subtoxic amounts may be applied (Klapper 1998b). In bottom sediments copper is present mostly in a less toxic carbonate form, so that benthic animals, the food for fish, may generally develop in a normal fashion. Nevertheless, the chemical elimination of the primary producers in general should be used only as a last option. Moreover, in mining lakes there is the potential for very acidic groundwater, coming from the overburden heaps in the form of dilute sulfuric acid, to re-dissolve toxic copper compounds in the sediments.

Water quality management in connection with the control of eutrophication has been described in several books, which are recommended for more detailed information: Cooke et al. (1993); Ryding and Rast (1989); Sas (1989); Harper (1992); Klapper (1991); Klapper and Scharf, in Brauer, ed. (1997); Busch et al. (1989).

9 Contamination

9.1 Decision Criteria for Treatment

Opencast mining holes have been used by mining companies and by the coal processing industry for dumping of overburden, ashes from power plants, coal dust from briquette factories, Winkler ash after phenol adsorption, wastes from smoulderies, tar, etc. They have even been used for deposition of municipal garbage and byproducts from other industries. Provided that there were no negative impacts on the water quality in the generating mining lakes and on the groundwater in the surroundings, this policy follows an old mining law, to give back the greatest area possible for agricultural and forestry use. This refilling with rubble and waste is mainly used to reduce the deficit of material remaining from the abstraction of coal. Regarding the water quality management of the mining lakes and water protection in general, complicated investigations of the character of the dumped materials have to be performed.

Along with the most recent progress in analytical methods, there is new knowledge of ecotoxicology. However, the problems generated by the disposal of different materials into mining lakes are complex. Each substance behaves differently under different environmental conditions such as pH, Eh, temperature, conductivity, matrices of other dissolved substances, etc., and with respect to solubility, degradability or persistence, bioaccumulation and other characteristics.

Today hundreds of compounds may be analysed in effluents from various deposits. However, with such data alone, the assessment of ecotoxicological impacts is very difficult. Therefore, besides the chemical analyses, ecotoxicological effects should be investigated with help of an inventory of indicator organisms with respect to saprobity, trophy, halobity, etc. With the components of the biocenosis, a good diagnosis of ecological health and toxicological impacts is possible.

Liquids deposited in old mining sites are generally more critical than solid materials. Liquids may spread into the groundwater to an extent depending upon the chemistry (sorption, biodegradation) of the substances and the permeability of the subsurface material.

A special technology that has been applied in the past in the case of very toxic or concentrated liquid wastes is high pressure injection into deep geological layers, e.g. into plate dolomite. However, examples are known where such hazardous substances reappear at large distances nearly undegraded or undiluted at the surface. Therefore, this deep well injection has been prohibited in Germany. Nevertheless, the dangers generated decades ago persist and still have to be monitored at several locations.

The water of the mining lakes in eastern Germany is polluted with hazardous substances not only from dumping sites. During dewatering of the uranium mines in the Ronneburg district, the Weisse Elster river was critically loaded with radionuclides. Where sulfur-acidified groundwater is flowing into to a mining lake, relatively high contents of heavy metals have been observed, sometimes at toxic concentrations. This depends on the geological composition of the area.

In the case of saltcoal mining the NaCl-content is very high in water. Salt may be curbed only by hydraulic counterpressure and by dilution.

During the microbial degradation of hazardous organic substances new metabolites may occur. The most important question for the assessment of impacts is whether or not degradation takes place at all. The speed of biodegradation may be increased by ecotechnological measures.

For possible utilization of secondary raw-material, the chemical industry has sometimes dumped distinct byproducts separately. However, when no option for a second use was taken, such single-substrate deposits prove to be more difficult to degrade compared with municipal mixed dumps. The latter have less hazardous substrates, more adsorbing ashes, degradable substrates, stimulating co-metabolisms, etc. Compounds, being quasi conserved by substrate inhibition because of high concentrations need to be sufficiently diluted and supplied with nutrients, oxygen and other factors limiting biodegradation.

Deposits of different substances may affect the fisheries in mining lakes in different ways. Organic degradable substances interfere with the oxygen balance. Salt causes meromictic stable stratification and anoxic deep waters, killing the eggs of the bottom-breeding Coregonid fish.

Deposits deliver substances such as heavy metals to the mining lakes, which may accumulate at different rates in the various organs of the fish. Ammonium in high concentrations, such as in the deposit at the bottom of the mining lake Großkayna near Merseburg, Germany, excludes fishes from the lake. Lipophilic compounds in particular accumulate in fatty flesh of fish, impairing the taste. Fat fishes, like eel and carp, are particularly affected by lipophilic matter.

9.2
Approaches for In-situ Remediation and Ex-situ Treatment of Contamination at Mining Lakes

A systematic record of all deposits in the mining lakes of eastern Germany and the assessment of their environmental impact revealed a great number of different conditions. Therefore, a scheme was developed outlining different approaches for treating the deposits and contamination in and around mining lakes, with methods for solving the problems in an ecologically acceptable and economically feasible ways (Table 9). For all cases mentioned in Table 9 examples occur in the new federal provinces of Germany. Usually combinations of different chemical, physical and microbiological conditions have to be assessed, to prepare plans for adequate treatment.

At the Nachterstedt mining hole a waste dump has been removed. This was very expensive, but was necessary for construction of a planned recreational center for water sports.

The isolation of a deposit at the side of the mining lake Hufeisensee in Germany is the target at Halle-Kanena. A huge mixed municipal and industrial landfill occupies a most of an opencast hole. The other part of the hole has been filled with overburden and the rest with groundwater. Experts were afraid that the lake would be impaired by the inflow of contaminated groundwater passing through the deposit (Carmienke et al. 1987; Glässer and Klapper 1992; Christoph 1995; Gläser 1995). However, a virtually water-tight soil cover, due to vegetation, allows little infiltration of water through the dump site. Fortunately, a deep trench in the mining lake is located adjacent to the landfill. The water seeping from the deposit only reaches the trench and does not mix with the rest of the water in the lake. The small monimolimnion obviously functions as a trap for hazardous substances. Limnological investigations show a high diversity of sensitive species in the lake. Therefore, bathing is now licensed in some areas of the lake, despite the accumulation of hazardous matter buried deep at the bottom of the lake (Scharf et al. 1995).

Under favourable conditions the deposit may be isolated within the lake itself. In the deepest parts of the lake the isolation of dumped waste is possible by capping with inert materials. A well-documented capping with sand has been performed in Hamilton Harbour, in Lake Ontario, Canada, to separate toxic sludges from the Hamilton steelwork from the overlying water (Zeman and Patterson 1997). In mining lakes very often nature provides this isolation without additional human activities. Where precipitated iron hydroxide and plankton biomass are covering the deposit in sufficiently thick layers, the best solution for the dumping site is not to interfere with the natural processes. On the other hand, if wastes had been dumped around the edges of the mine, it has to be considered that waves and erosion might again expose the dump, even with thick layers of covering materials. A total subhydric incapsulation, including the lake surface, was the final solution of one of the most complicated deposits in a mining lake. The mining lake Silbersee in Germany was used for dumping different matter from the Wolfen film factory. From the original volume of $2.7 \times 10^6 m^3$ today $1.1 \times 10^6 m^3$ is occupied by spoiled ashes, $0.4 \times 10^6 m^3$ by carbonate sludge from a water treatment plant and $1 \times 10^6 m^3$ by lignine and cellulose sludge from a cellulose factory. The latter sludges are of a pudding-like consistency, with more than 90 % water content. A high content of sulfur led to gas emissions of sulfur hydrogen, mercaptane and other stinking and poisonous gases. Trials with an ex-situ pilot plant led to a solid-liquid separation. But no plants are growing on the solid material and the liquid phase did no receive license as an effluent.

Table 9. Outline of approaches to treat contaminated deposits at mining lakes

Removal of the waste dump	Isolation of the contamination near or in the lake		Restoration of the contamination			
			ex-situ treatment		in-situ treatment	
	general	*subhydric deposition*	*off site* in existing treatment plant (transport of matter is necessary)	*on site* mobile treatment plant	*partitioned* enclosures limnocorrals subhydric straw reactor	*lake sites* mixolimnion monimolimnion hypolimnion sediments
transfer of the waste to a special deposit	covering by plastic sheets or by soil with evaporating vegetation	profundal: capping with sand, ash or overburden; covering with matter from the pelagial: dead algae, Fe-hydroxide	physical methods sedimentation, flotation, stripping, adsorption, combustion		precipitation and transfer to the permanent sediment	
sorting, screening, deposition of only hazardous parts of the waste	technical capsulation by sheet piling or grout curtain		chemical methods precipitation, dissolution, ion-exchange, oxidation, extraction		neutralisation (liming) change in solubility	
					abatement of H_2S with Fe^{3+}, NO_3- and liquid O_2	
drying; combustion	geohydraulic: inverted wells preventing groundwater influx	littoral: covering with soil, planting macro-phytes	biological methods mixing reactor, oxic: activated sludge (with P) solid bed reactor, oxic: trickling filter, contact aerator		aeration: surface aeration deep water aeration destratification	
utilization as a secondary resource						
pumping of liquid wastes (e.g. tar) to a treatment	lowering well in the dump preventing outflow from the deposit	water surface: covering with biofilters to prevent odour	solid bed reactor, anoxic: microbial desulfurication		incorporation in biomass; metabolisation; addition of limiting nutrients	
	treatment of the well water as sewage	covering with floating reed				

After all experiments had failed, the new target was the encapsulation of the material. Fortunately, groundwater contamination may be excluded in this case, because the fine-grained materials are nearly watertight. The deposit is like a sealed capsule in the regional groundwater field and the groundwater flows around it without causing significant pollution. Where the sludge reached the surface of the lake, 3-ha has been covered with biofilters – bags, filled with a mixture of wood sticks and foamed polystyrole chips (Fig. 19). The remaining approximately 1-m deep or shallower lake area is kept aerobic with the help of floating rotor aerators to avoid further H_2S emissions (Schmitz 1996). Desired spreading of floating reed, as in the mining lake Haselbach 1 in Germany, needs a surprisingly long time. This is probably due to the sulfur hydrogen, poisoning the cells of the rhizomes. The new target for this lake is to form a green covered area, protected against humans and reserved for nature and nature observation.

Nearly all ex-situ treatments, either off-site in existing treatment plants or on-site immediately at the deposit, are very expensive and generally not satisfactory with respect to the through flow. The off-site process is expensive because of the necessary transport of the polluted media to existing facilities, such as sewage treatment plants or incinerating plants.

For the on-site treatment special facilities have to be installed and operated for all necessary steps of physical, chemical and biological purification. These facilities are available as modules that may be combined according to the technological demand. For on-site operation, electricity and pipes have to be installed from the deposit to the treatment modules and from the treatment plant to polishing and accumulation ponds, e.g., for oxidation. Moreover, on-site operation includes human attendance during night and day. The process steps are mainly the same for on-site and off-site treatment plants and are selected according to the matter to be treated.

The most interesting developments are different in-situ treatments. These may be classified as part of the modern field of ecotechnology, i.e., biotechnology on the level of the ecosystem. With scientific knowledge of the natural functions within these ecosystems, these approaches aim only to help the system help itself by metabolisation and cometabolisation, incorporation, bioaccumulation, bioflocculation and sedimentation of the treated materials. All these processes may be identified as self-purification. To stimulate aerobic processes, oxygen has to be supplied. For anaerobic processes, such as microbial neutralisation by desulfurication, oxygen has to be kept away with help of hydraulic isolation or biochemical oxygen consumption.

The developing technologies are at the stage of pilot scale experiments in artificially separated parts of the water body such as enclosures, limnocorrals or in submerged reactors like the straw-cage for heterotrophic denitrification mentioned above. On a full, technical scale those lake sites with the most suitable environmental conditions have to be selected depending on the targets to be met. Clearly, sediments and the deep waters are suitable for anoxic treatments, while the surface waters or destratified or aerated parts of the water body are more suitable for oxic degradation.

For decades effluents from the lignite pyrolysis plants formerly operated in Central Germany have contaminated the region's groundwater and surface water. In order to develop remediation strategies, the case study of a pyrolysis waste water deposit was used to investigate the complex characterisation of the deposit as well as the fundamental chemical and biological reactions of pyrolysis waste water altered by storage. The group of anthropogenic humic substances (AHS), formed by abiotic oxidative polymerisation from monomeric phenols, was perceived as determining the chemical behaviour and the biological effects (Stottmeister et al.1998).

The deposit in a former open cast mine, located in Saxony-Anhalt, near the city of Zeitz (village Trebnitz), showed the following characteristics when the studies began in 1992:

- area 9 ha,
- water volume 2 million m^3,
- maximum depth 27 m,
- visibility depth 0.03 m,
- oxygen content of the water 0 mg l^{-1}.

A strong odour of organic sulfur compounds irritated the inhabitants of the region.

The dark brown water body showed a stratification with concentration of total phenolic compounds between 7 to about 100 mg l^{-1} in the upper zone (0–10 m) and of more than 200 mg l^{-1} in the deeper ones (15–24 m). Ammonia was detected in the same concentration range (up to 250 mg l^{-1}). The maximum of the COD (chemical oxygen demand) was 2,290 mg l^{-1}, the maximum DOC (dissolved organic carbon) 690 m l^{-1}in 20 m depth.

A traditional ex situ water treatment was not practicable. A new unconventional in situ remediation strategy was developed and tested in *in situ* enclosures (see Fig. 20 and 21) (Stottmeister et al. 1999). The positive results of these experiments were used for a full scale remediation of the deposit (Stottmeister et al. 2000).

The strategy can be described very shortly as follows: the initiation of the biological self purification in a stable stratified water body with an aerobic upper and an anaerobic deeper zone and a sediment area (application of the "pontos euxinos" effect).

In detail, the following steps of "habitat engineering" were carried out:

- flocculation of black AHS-macromolecules by iron-(III)-chloride solution (3200 m^3 40%) at pH 4–5, resulting in a sedimentation of the flocs and settling on the ground;
- neutralisation of the formed clear uncoloured water body with 50 % of the former DOC (pH 7–8) with limestone suspension (2,200 m^3 20%);

- addition of phosphoric acid in steps (3 x 0.8 m^3 75 %).

The most sensitive step was the injection of the chemicals into the water body because the specific water density had to be calculated for a stable stratification. Like in the enclosure experiments, after flocculation of the toxic and oxygen consuming AHS macromolecules the clear water was immediately saturated with oxygen down to 3–4 m (depending on the season) and the microbiological degradation activity started after neutralisation. The addition of phosphorus (the limitation of P was caused by the addition of Fe(III)-salt) initiated an intensive algae growth with photochemical oxygen production and additional sorption capacity for residues of AHS.

In only three years (1998–2001) both the biotic and abiotic processes together resulted in the formation of a non-toxic ecosystem with a "normal" hydrobiological biodiversity in the upper aerobic zone (down to 6 m). No phenols are detectable in the surface zone (down to 5 m). The phenols are eliminated also to 95 % in the depth of 20 m indicating anaerobic (methanogenic and iron-III-reducing) activities.

The long-term behaviour of this first ever realised "enhanced natural attenuation"-process of an industrial waste water deposit is under studies.

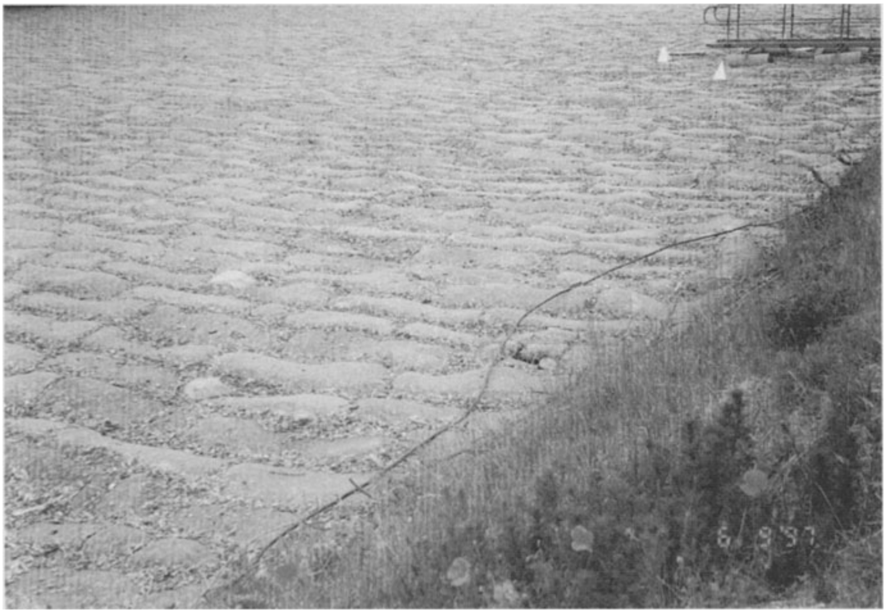


Fig. 19. Deposit of chemical wastes in a former opencast mine at Wolfen, Germany. The surface is covered with biological filters protecting against H_2S emissions (photo: U. Stottmeister)

Fig. 20. Installation of an enclosure for sediment investigation in the Schwelvollert deposit in Saxony-Anhalt, Germany (field studies of the UFZ Centre for Environmental Research, Leipzig, photo: (U. Stottmeister)

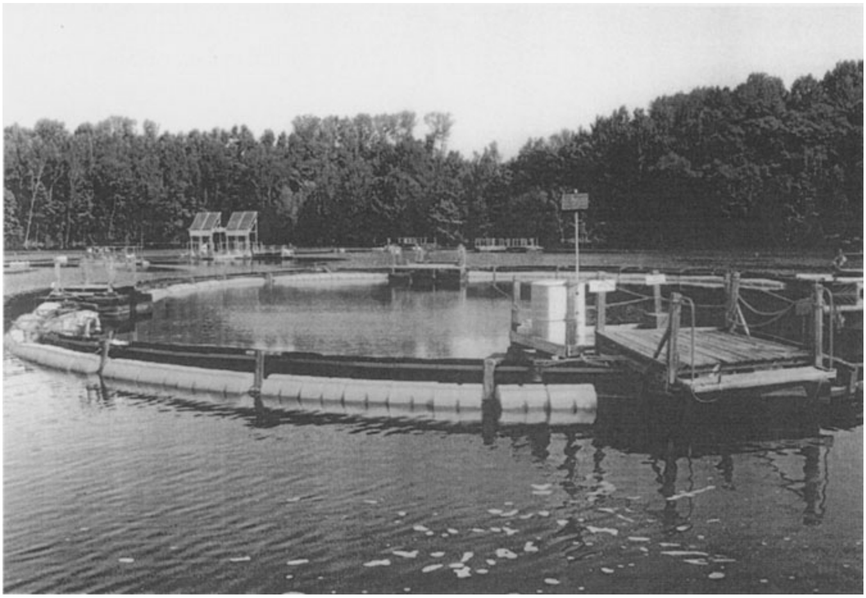


Fig. 21. Field laboratory with several enclosures in a deposit of wastewaters from lignite carbonization (UFZ Centre for Environmental Research, Leipzig, photo: U. Stottmeister)

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