ON THE RELEVANCE OF MEROMIXIS IN MINE PIT LAKES[1]

Bertram Boehrer[2] and Martin Schultze[3]

Abstract. Worldwide the number of mine pit lakes is growing. Due to their steep slopes, their relatively great depth and their exposure to highly mineralized inflows, a remarkable portion of these lakes tend to be meromictic. Meromixis indicates that the deepest part of the water body - the monimolimnion - is excluded from seasonal overturn and thus from contact to the atmosphere. Although this phenomenon is not common in natural lakes, it is well known. Meromixis is accompanied by some important consequences with respect to water quality: (1) strong anoxia in the monimolimnion, (2) enrichment of products of microbial decay in the monimolimnion and (3) occurrence of hydrogen sulfide and precipitation of metal sulfides in the monimolimnion. In some cases, advantage can be taken from the enrichment of substances in the monimolimnion due to the very low exchange with the rest of the lake. As a consequence, hazards may be avoided. On the contrary, if a sudden total overturn happens, e.g. induced by a heavy storm, fish kills and other catastrophic events may be the consequence.

Additional Key Words: management of water quality, remediation

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[2] Bertram Boehrer is limno-physicist, Department of Lake Research of the UFZ Centre for Environmental Research Leipzig-Halle, Magdeburg, D-39114, Germany, [3] Martin Schultze is limno-chemist, Department of Lake Research of the UFZ Centre for Environmental Research Leipzig-Halle, Magdeburg, D-39114, Germany.

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Introduction

In Germany, pit lakes resulting from lignite surface mining represent a considerable portion of the total number of lakes (Geller et al. 2000, Nixdorf et al. 2001). In recent years, 120 new lakes have been created (Krüger et al. 2002). Also in other countries, e.g. in the Czech Republic or Poland, Australia, France, U.K., lakes form in the residual pits of former lignite mines (Stottmeister et al. 2002, , Denimal et al. 2005, Doupe and Lymery 2005, Younger 2005). Worldwide we see a growing awareness for the environmental concerns connected with pit lakes, of which many originate from ore mining (e.g. Davis and Ashenberg 1989, Miller et al. 1996, Eary 1999, Castro and Moore 2000, Parshley and Bowell 2003, Breckenridge et al. 2005).

Exposed to the same annual cycle, the lake surface temperature follows the annual temperature cycle of the atmosphere. Wind can cause a heat transfer to a limited depth in the lake. As a consequence, an episodically mixed warm water layer “epilimnion” can occur above the colder “hypolimnion” during summer months (see Fig. 1). Such lakes are seasonally stratified, until lower surface temperatures permit a deeper mixing. In most natural lakes, a complete overturn is accomplished at some time during the year and water properties are homogenized over the entire water column. Such lakes are called holomictic. Shallow lakes do not form a hypolimnion and can be overturned several times during the year.

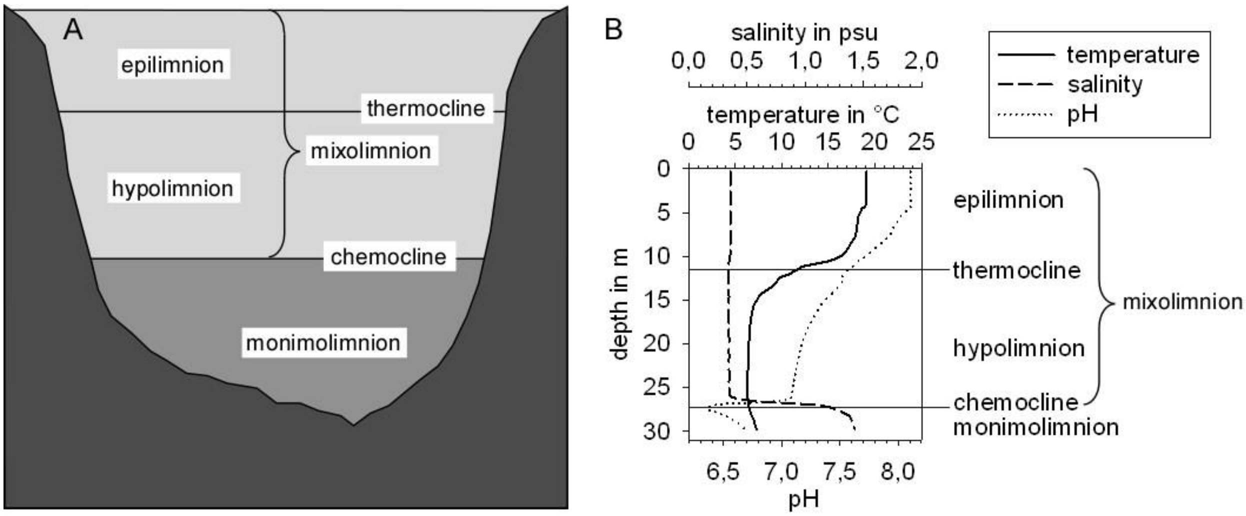

Figure 1. Illustration of the terminology of stratification in meromictic lakes (details see text): panel A - generalized cross-section through a meromictic lake (under conditions of temperate climate during summer, i.e. the occurrence of thermal stratification in the mixolimnion); panel B - profiles of temperature, salinity and pH at sampling site XP4 in Lake Goitsche (Germany) on August 23rd, 2005 (psu – practical salinity unit, Fofonoff and Millard 1983; for further information on Lake Goitsche see Boehrer et al. 2003)

On the contrary in a number of lakes, we find a bottom water of increased salinity. If the density is high enough, it can resist the deep recirculation and thus the lake stays permanently stratified. It is called meromictic (Findenegg 1933, 1935). The bottom water “monimolimnion” only shows limited exchange of dissolved matter with the “mixolimnion” across the “chemocline”, and thus can develop chemical properties very different to the mixolimnion. A number of further peculiarities is connected with a permanent stratification. High concentrations of living organisms as well as high turbidity due to precipitating minerals and settling material from above are commonly found in this transition zone.

This contribution aims at comprising the recently acquired knowledge on stratification in mining lakes originating from mining for both ore as well as coal and lignite. In addition, the geologic environment covers both hard rock and sandy material, which is of great importance for the later basin geometry of the lakes, and the connection to the groundwater flow.

Meromixis in natural lakes

Meromixis is known from natural lakes. Traditionally, three classes of meromixis are distinguished (Hutchinson 1957) according to the mechanisms creating a large enough density difference between mixolimnion and monimolimnion. Only if the stratifying processes continuously contribute to the stability of the water column sufficiently to overcome the destabilizing effect of mixing processes, a permanent stratification is sustained in a dynamic equilibrium.

Ectogenic meromixis

This type of meromixis is caused by introduction of salt water into a freshwater lake or of fresh water into a salt water lake at the lake surface. Examples are Lake Tokke, Lake Botnvatn and Lake Powell (Strøm 1963, Sanderson et al. 1986), where sea water was trapped in a bay due to falling sea level or the elevation of the land after glaciation. Due to its lower density, freshwater entering the basin floated on top of the salt water and never mixed entirely. Another example was Lake Mono which stayed meromictic for 6 years when the inflow of freshwater was reestablished (Jellison et al. 1998). A last example being mentioned Lake Schalkenmehrener Maar where saline water from de-iced roads caused a permanent stratification (Scharf and Oehms 1992).

Crenogenic meromixis

This meromixis class results from the entrance of saline ground water into a freshwater lake. Examples are Lake Monoun, Lake Nyos and Lake Kivu which have their deep water loaded with dissolved substances from the lake bed due to volcanic activity in the area (Halbwachs et al. 2004). Another example is Lago Cadagno (Del Don et al. 2001) which receives groundwater from different geologic formations at the surface and at the bottom, respectively. Its location at the high altitude in the Alpine Mountains and its consequently long lasting annual ice cover may also contribute to its meromixis (Del Don et al. 2001).

Biogenic meromixis

This type of meromixis is caused by enrichment of dissolved substances in the monimolimnion as a consequence of biological activity. The meromictic lakes of Carintia (Austria) are considered to be meromictic as a consequence of photosynthesis close to the surface and microbial decay of organic substances (respiration) at the lake bottom. Subsequent dissolution of the resulting end products into the lake water contributes to the density of the deep water and hence can create meromixis (Findenegg 1935). Scharf and Oehms (1992) reported temporary meromixis for Lake Meerfelder Maar as a consequence of eutrophication caused by waste water and the processes described above. When the lake was re-mediated the monimolimnion disappeared during overturn.

This mechanism of biogenic meromixis may be intensified by a secondary process coupled to photosynthesis and respiration. Under favorable conditions, photosynthesis can raise the pH in the epilimnion to a level that precipitation of calcite can occur. If this calcite falls into a monimolimnion of high concentrations of accumulated CO_2, it can be re-dissolved into the lake water as described by Rodrigo et al. (2001) for Lake La Cruz in Spain.

A special form of biogenic meromixis occurs in small lakes in northern regions where an iron cycle stabilizes the stratification (Kjensmo 1962, Merilainen 1970, Campbell and Torgensen 1980, Hongve 1997). Iron can enter a lake with a groundwater inflow. In the oxic mixolimnion iron can be further oxidized and precipitated. After sedimentation into an anoxic monimolimnion, microbial reduction can facilitate the re-dissolution in the monimolimnion water. In this case, mixing processes between mixolimnion and monimolimnion are very ineffective in terms of removing stratification, as the contact between oxic waters and iron rich monimolimnion sustains the iron cycle.

The influence of lake morphometry on meromixis is evident, though poorly understood and hard to quantify. Walker and Likens (1975) used the relative depth z_r (ratio of maximum depth and root of surface area) to indicate a “predisposition” for meromixis. Also Lemmin (1995) emphasized the relevance of morphometry. However the mechanisms are beyond simple ratios of numbers. They depend on the shape of the lake basin, which may be favorable for protecting a monimolimnion from erosion by lake wide currents and turbulence, e.g. submersed river channels may facilitate renewal of deep water without removing the density stratification in the main body of the lake.

Meromixis in pit lakes

There is a relatively high number of publications reporting meromixis in pit lakes (Table 1). This indicates that some properties of pit lakes are more favorable for creating meromixis than conditions in natural lakes. However the classes of meromixis for natural lakes are also applicable for mining lakes.

Lyons et al. (1994) and Castro and Moore (2000) pointed out that meromixis may occur in pit lakes more commonly than in natural lakes, because of the relatively small ratio of surface area to depth. Doyle and Runnells (1997) compared data of four pit lakes and found two of them were meromictic and two were seasonally mixed, although the latter also had high relative depths. Rücker et al. (1999) and Boehrer et al. (2003) reported meromixis in pit lakes which have low relative depth (Lugteich and Lake Goitsche).

The pit lake in the former Island Copper Mine (Vancouver Island, Canada) can clearly be classified as ectogenically meromictic. Sea water was used to fill most of its volume. The final cap was formed by a thin freshwater layer (Fisher 2002). There are also lakes which show crenogenic meromixis: the lakes in the former lignite mine Merseburg-Ost (Germany; Böhrer et al. 1998, von Rohden and Ilmberger 2001) and Lake Hufeisensee (Germany; Schreck 1996). Saline groundwater from the deeper underground entered these pit lakes. This was facilitated by the dewatering during the mining operations and during the remediation and by the mining itself. Also the meromixis in Lake Goitsche (Germany) is connected to groundwater inflow (Boehrer et al. 2003). The high mineralization results from pyrite oxidation in the ground.

Table 1. Meromixis reported in pit lakes

Lake (country) - mined material	Morphometric data*	Reasons for meromixis**	References
Berkeley Pit (USA) - copper	A: - V: >110[†] z_{max}: 220[†]	- formation of a less mineralised mixolimnion by - inflow of less mineralised water at the lake surface[†] - enrichment of iron and sulfate due to precipitation /sedimentation of secondary iron minerals in the mixolimnion, their re-dissolution in the monimolimnion and ongoing pyrite oxidation at the pit walls in the monimolimnion by ferric iron[†]	Davis and Ashenberg 1989 Robins et al. 1997 Doyle and Runnells 1997 Jonas 2000 Gammons et al. 2003 Madison et al 2003 Pellicori et al. 2005
Island Copper Mine (Canada) - copper	A: 1.72 V: 241 z_{max}: >400	- first filling step with sea water (93% of volume) and second filling step with fresh water (7% of volume)	Fisher et al. 2000 Muggli et al. 2000 Fisher 2002 Poling et al. 2003 Stevens et al. 2005 Boehrer and Stevens 2005
Spenceville Copper Pit (USA) - copper	A: 0.002 V: 0.023 z_{max}: 17	- enrichment of substances due to evaporation - accumulation of iron and other substances in the monimolimnion due to microbial decay of organic compounds	Levy et al. 1997
Rävlidmyran Pit (Sweden) - zinc, copper, lead, silver, gold	A: 0.049 V: 0.53 z_{max}: 28.9	- primary filling with highly mineralised water caused by elution of pit walls and inflow of water of high TDS concentration due to pyrite oxidation[††] - accumulation of iron and other substances in the monimolimnion[††]	Lu et al. 2003 Lu 2004

Table 1. continued

Lake (country) - mined material	Morpho-metric data*	Reasons for meromixis**	References
Anchor Hill Pit (USA) - gold, silver, copper, lead, zinc	A: 0.018 V: 0.26 z_{max}: 26	- measures to neutralize the lake (liming, addition of organic material to stimulate reductive microbial processes for alkalinity production	Lewis et al. 2003
McLaughlin Gold Mine, soth pit lake (USA) - gold	A: - V: - z_{max}: 85.3	- intrusion of saline water by subrosion of salt strata in the deeper underground - accumulation of CO_2 in the monimolimnion caused by thermal springs at the lake bottom	Rytuba et al. 2000
Brenda Pit (Canada) - molybdenum	A: 0.38 V: 20.7 z_{max}: >140	- no clear information given in the references	Stevens and Lawrence 1997 Hamblin et al. 1997 Stevens and Lawrence 1998 Hamblin et al. 1999
Gunnar (Canada) 1997	A: 0.07 V: - z_{max}: 110	- no clear information given in the reference	Doyle and Runnells
pit lake in southeast Tennessee[†††] (USA)	A: 0.08 V: 2.1 z_{max}: 60	- dilution of the mixolimnion by through flow of a stream[††] - primary filling with highly mineralised water caused by elution of pit walls and inflow of water of high TDS concentration due to pyrite oxidation[††]	Colarusso et al. 2003
St Louis (France) - coal	A: - V: - z_{max}: 60	- elution of pit walls and inflow of ground water of high TDS concentration due to pyrite oxidation[††]	Denimal et al. 2005
Fouthiaux (France) - coal	A: - V: - z_{max}: 37	- elution of pit walls and inflow of ground water of high TDS concentration due to pyrite oxidation[††]	Denimal et al. 2005

Table 1. continued

Lake (country) - mined material	Morpho-metric data*	Reasons for meromixis**	References
Mining Lake 111 (Germany) - lignite	A: 0.1 V: 0.5 z_{max}: 10.2	- inflow of ground water of high TDS concentration due to pyrite oxidation	Karakas et al. 2003
Goitsche (Germany) - lignite	A: 13.3 V: 213 z_{max}: 47	- inflow of ground water of high TDS concentration due to pyrite oxidation	Boehrer et al. 2003
Waldsee (Germany) - lignite	A: 0.003 V: - z_{max}: 5	- inflow of ground water of high TDS concentration due to pyrite oxidation - accumulation of iron and DIC in the monimolimnion	Rücker et al. 1999 Schimmele 1999
Lugteich (Germany) - lignite	A: 1.7 V: 3.5 z_{max}: 10	- inflow of ground water of high TDS concentration due to pyrite oxidation - accumulation of iron and DIC in the monimolimnion	Rücker et al. 1999
Moritzteich (Germany) - lignite	A: 0.16 V: 1.2 z_{max}: 17.5	- inflow of ground water of high TDS concentration due to pyrite oxidation - accumulation of iron and DIC in the monimolimnion	Stellmacher 2004
Hufeisensee (Germany) - lignite	A: 0.7 V: 6.1 z_{max}: 29	- intrusion of saline water by subrosion of salt strata in the deeper underground	Schreck 1998 Maiss et al. 1998 Stottmeister et al. 1999
Merseburg-Ost 1a (Germany) - lignite	A: 2.8 V: 30 z_{max}: 27	- intrusion of saline water by subrosion of salt strata in the deeper underground	Böhrer et al. 1998 von Roden and Ilmberger 2001 Boehrer et al. 2006
Merseburg-Ost 1b (Germany) - lignite	A: 2.3 V: 47 z_{max}: 36	- intrusion of saline water by subrosion of salt strata in the deeper underground	Böhrer et al. 1998 von Roden and Ilmberger 2001 Boehrer et al. 2006

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* A – surface area in 10^6 m^2, V – volume in 10^6 m^3, z_{max} - maximal depth in m

** TDS – total dissolved solids, DIC – dissolved inorganic carbon

† presented information taken only from Pellicori et al. 2005

†† interpretation of the information in the references by Boehrer and Schultze

††† name of the lake is not given in the reference

While there are pit lakes that clearly can be attributed to one particular meromixis class, other cases show a stratification caused by more than one mechanism, e.g. from rock weathering highly mineralized water can enter a lake as surface runoff and as groundwater.

Lake Moritzteich (Germany; Stellmacher 2004) and (formerly) Lake Waldsee (Germany; Rücker et al. 1999, Schimmele 1999) are characterized by an acidic mixolimnion and a neutral monimolimnion. High concentrations of DOC and iron in the monimolimnion point at a biogenic meromixis, while entering groundwaters are indicative for a crenogenic meromixis.

Similar is true in Lake Goitsche (Fig. 1 panel B) where biological processes contribute their part to the meromixis. The pH-minimum in the chemocline is the result of the iron cycle described above for small meromictic lakes in Scandinavia. The precipitation of ferric iron releases acidity in the chemocline causing the local decrease of pH. However, the main reason for meromixis in Lake Goitsche is supposedly the entrance of groundwater.

Processes in meromictic lakes and their benefits and risks

Usually meromixis is connected with an anoxic monimolimnion resulting from respiration of organic material, only marginal photosynthetic activity in the monimolimnion, and the absence of gas exchange with the atmosphere. A series of other chemical transformation, e.g. oxidation of ferrous to ferric iron (Madison et al. 2003) may contribute to the oxygen depletion in the monimolimnion. On the contrary, a lot of substances are enriched in the monimolimnion from precipitation out of the mixolimnion, or release from the sediment surface. The further transport into the water column above is limited by the small exchange rates across the density gradient of the chemocline (von Rohden and Ilmberger 2001). The transport rates can be as small as molecular diffusion.

The above mentioned Island Copper Mine Lake relies on the small exchange between monimolimnion and mixolimnion (Fisher 2002). The meromixis limits the transport of acidity and heavy metals, which were removed from the lake water by artificial eutrophication, back into the mixolimnion (Poling et al. 1997). In the lakes of the former mine Merseburg-Ost, the meromictic conditions are expected to contribute to the irreversible removal of phosphorus from the water body (Schultze et al. 2005). In this way, undesirable eutrophication could be avoided.

The accumulation of CO_2 in the meromictic lake Nyos in Africa resulted in a limnic eruption where more than thousand people were killed by a sudden release of the accumulated gas (Halbwachs et al 2004). Murphy (1997) made some predictive calculations, if such a catastrophe can happen in pit lakes. He found that such an event is not very likely, but cannot be excluded.

However, partial or complete overturns caused by heavy storms can release enriched monimolimnetic substances into the mixolimnion. For example if metals are missing to form sulfides, high H_2S can accumulate in a monimolimnion. Concentrations of more than 300 mg/L H_2S are found in the monimolimnion of Lake Hufeisensee, Germany. A sudden release of larger amounts into the mixolimnion would cause fish kills through its toxicity, or later through oxygen depletion following oxidation of H_2S through bacteria.

Both for taking advantage of meromixis as well as for disaster prevention, prognostication tools for meromixis would be mandatory. Over the last few years, detailed observational investigations have been conducted. Both, transports through extremely high density stratification in monimolimnia (von Rohden and Ilmberger, 2001) and the annual erosion of the chemocline by the deep circulation (Boehrer et al. 2006) have been measured to gain a quantitative approach to stability of meromixis. Such results need to feed into numerical models for the meromixis prediction (e.g. Stevens and Lawrence 1998, Jellison et al. 1998, Böhrer et al. 1998). However up to date, none of the meromixis models had included the effect of chemical transformation, which is an interesting, often the decisive and definitely the most challenging contribution keeping a lake permanently stratified.

Summary

Pit lakes are more prone to become meromictic than natural lakes. Various processes and circumstances contribute to the formation and stabilization of the permanent stratification. The inflow of highly mineralized water as a consequence of pyrite oxidation and the favorable surface to depth ratio can be expected to be the most important factors to support meromixis. While meromixis is accompanied by a number of risks, it also provides options to prevent and manage environmental impacts of hazardous mine wastes and mine water. As a consequence, the understanding of meromixis and the quantification of its stability is an important step for managing and protecting our environment.

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