

ON THE RELEVANCE OF MEROMIXIS IN MINE PIT LAKES¹

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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

¹ Poster paper presented at the 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502

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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 Howell 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.

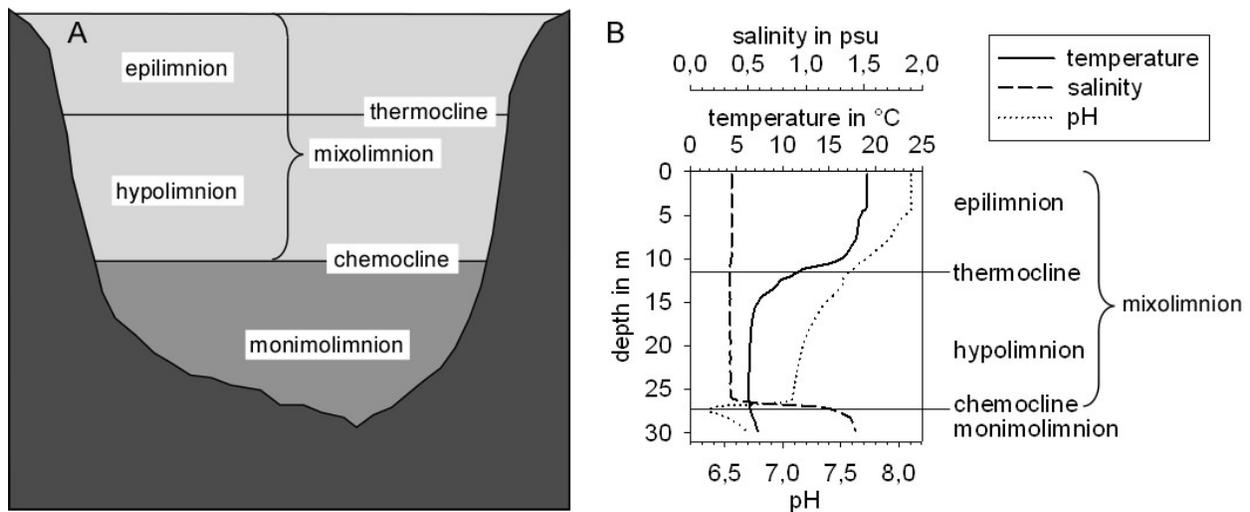


Figure 1. Illustration of the terminology of stratification in meromictic lakes (details see text): panel A - generalized cross-section through a meromictic lake (under conditions of temperate climate during summer, i.e. the occurrence of thermal stratification in the mixolimnion); panel B - profiles 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 CO₂, 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	Morpho- metric 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 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

* 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 CO₂ 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 H₂S can accumulate in a monimolimnion. Concentrations of more than 300 mg/L H₂S 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 H₂S 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.

Literature Cited

- Böhrer, B., H. Heidenreich, M. Schimmele and M. Schultze 1998. Numerical prognosis for salinity profiles of future lakes in the opencast mine Merseburg-Ost. Intern. J. Salt Lake Res. 7, 235-260.
- Boehrer, B., M. Schultze, S. Liefold, G. Behlau, K. Rahn, S. Frimel, U. Kiwel, B. Kuehn, I. Brookland and O. Büttner 2003. Stratification of mining Lake Goitsche during flooding with river water. p. 223-231. *In: Tailings and Mine Waste '03*. Swets and Zeitlinger, Lisse.
- Boehrer, B. and C. Stevens 2005. Ray waves in a pit lake. *Geophys. Res. Lett.*, 32 (24)
- Boehrer, B., U. Kiwel, K. Rahn, M. Schultze 2006. Deep recirculation inhibited by freshwater introduction to meromictic salt lakes (submitted)
- Breckenridge, L., A. Hudson, P. Brown, and M. Henderson 2005. Hydrogeologic investigation of the Gold Reserve Incorporated Brisas del Cuyuni Concession in Southeast Venezuela. p. 459-465. *In: J. Loredó and F. Pendas (eds.). Proc. 9th International Mine Water Association Congress (Oviedo, Spain, September 5-7, 2005)*, Dept. Explotacion y Prospeccion de Minas, Univ. of Oviedo on behalf of the Intern. Mine Water Association, Oviedo, Spain.
- Campbell, P. and T. Torgensen 1980. Maintenance of iron meromixis by iron redeposition in a rapidly flushed monimolimnion. *Can. J. Fish. Aquat. Sci.* 37, 1303-1313.
- Castro, J.M. and J.N. Moore 2000. Pit lakes: their characteristics and the potential for their remediation. *Environ. Geol.* 39, 1254-1260.
- Colarusso, L.A., J.A. Chermak, J.C. Priscu and F.K. Miller 2003. Modeling pit lake water column stability using Ce-Qual-W2. p. 213-222. *In: Tailings and Mine Waste '03*. Swets and Zeitlinger, Lisse.

- Davis, A. and D. Ashenberg 1989. The aqueous geochemistry of the Berkeley Pit, Butte, Montana, U.S.A. *Appl. Geochem.* 4, 23-36.
- Del Don, C., K.W. Hanselmann, R. Peduzzi and R. Bachofen 2001. The meromictic alpine Lake Cadagno: Orographical and biogeochemical description. *Aquat. Sci.* 63, 70-90.
- Denimal, S., C. Bertrand, J. Mudry, Y. Paquette, M. Hochart and M. Steinmann 2005. Evolution of the aqueous geochemistry of mine pit lakes – Blanzky-Montceau-les-Mines coal basin (Massif Central, France): origin of sulfate contents; effects of stratification on water quality. *Appl. Geochem.* 20, 825-839.
- Doyle, G.A. and D.D. Runnells 1997. Physical limnology of existing mine pit lakes. *Mining Engineering* 49, 76-80.
- Doupe, R.G. and A.J. Lymery 2005. Environmental risks associated with beneficial end use of mine lakes in southwestern Australia. *Mine Water and the Environment* 24, 134-138.
- Eary, L.E. 1999. Geochemical and equilibrium trends in mine pit lakes. *Appl. Geochem.* 14, 963-987.
- Findenegg, I. 1933. Alpenseen ohne Vollzirkulation. *Intern. Rev. Ges. Hydrobiol. Hydrograph.* 28, 295-311.
- Findenegg, I. 1935. Limnologische Untersuchungen in Kärtener Seengebieten. *Intern. Rev. Ges. Hydrobiol. Hydrograph.* 32, 369-423.
- Fisher, T.S.R. 2002. Limnology of the meromictic Island Copper Mine pit lake. PhD-thesis, Univ. British Columbia, Vancouver, Canada.
- Fisher, T.S.R. and G.A. Lawrence 2000. Observations at the upper halocline of the Island Copper Pit Lake. p. 413-418. In: Lawrence, G.A., R. Pieters and N. Yonemitsu (eds.): Fifth International Symposium on Stratified Flows, 10-13 July 2000, Vancouver, British Columbia. Department of Civil Engineering, University of British Columbia, Vancouver.
- Fofonoff, N.P. and R.C. Millard jr. 1983. Algorithms for commutation of fundamental properties of seawater. UNESCO technical papers in marine science 44.
- Gammons, C.H., S.A. Wood, J.P. Jonas, and J.P. Madison 2003. Geochemistry of the rare-earth elements and uranium in the acidic Berkeley Pit lake, Butte, Montana. *Chem. Geol.* 198, 269-288.
- Geller, W., K. Friese, P. Herzprung, R. Kringel and M. Schultze 2000. Limnology of sulfur-acidic lignite mining lakes II: Chemical main constituents and buffering systems. *Verh. Intern. Verein. Limnol.* 27, 2475-2479.
- Halbwachs, M., J.-C. Sabroux, J. Grangeon, G. Kayser, J.C. Tochon-Danguy, A. Felix, J.C. Beard, A. Vilevielle, C. Vitter, P. Richon, A. Wüest. and J. Hell 2004. Degassing the "Killer Lakes" Nyos and Monoun, Cameroon. *EOS* 85, 281-284.
- Hamblin, P.F., C.L. Stevens and G.A. Lawrence 1997. Vertical transport in Brenda Mines pit lake. p. 367-383. *In: Proceedings of the Fourth International Conference on Acid Rock Drainage, May 31 – June 6 1997, Vancouver, B.C. Canada.*

- Hamblin, P.F., C.L. Stevens and G.A. Lawrence 1999. Simulation of vertical transport in mining pit lake. *J. Hydraul. Eng.* 125, 1029-1038.
- Hongve, D. 1997. Cycling of iron, manganese, and phosphate in a meromictic lake. *Limnol. Oceanogr.* 42, 635-647.
- Hutchinson, G.E. 1957. A treatise on limnology – Vol. 1. J. Wiley and sons, New York.
- Jellison, R., J. Romero and J.M. Melack 1998. The onset of meromixis during restoration of Mono Lake, California: Unintended consequences of reducing water diversions. *Limnol. Oceanogr.* 43, 706-711.
- Jonas, J. 2000. Current seasonal limnology of the Berkeley Pit-Lake. p. 359-366. *In: Proceedings Fifth International Conference on Acid Rock Drainage. Society of Mining, Metallurgy, and Exploration (SME), Littleton.*
- Karakas, G., I. Brookland and B. Boehrer 2003. Physikal characteristics of Acidic Mining Lake 111. *Aquat. Sci.* 65, 297-307.
- Kjensmo, J. 1962. Some extreme features of iron metabolism in lakes. *Schweiz. Z. Hydrol.* 24, 244-252.
- Krüger, B., A. Kadler and M. Fischer 2002. The Creation of Post-Mining Landscapes of Lignite Mining in the New Federal States. *Surface Mining - Braunkohle and other minerals* 54, 161-169.
- Lemmin, U. 1995. Limnologie physique. p. 61-106. *In: Pourriot, R. and M. Meybeck (eds.): Limnologie générale. Masson, Paris.*
- Levy, D.B., K.H. Custis, W.H. Casey and P.A. Rock 1997. The aqueous geochemistry of the abandoned Spenceville Copper Pit, Nevada County, California. *J. Environ. Qual.* 26, 233-243.
- Lewis, N.M., K.W. Wangerud, B.T. Park, S.D. Fundingsland and J.P. Jonas 2003. Status of in situ treatment of Anchor Hill Pitt lake, Gilt Edge Mine Superfund site, South Dakota, USA. p. 779-788. *In: Farrell, T. and G. Taylor (eds.): Sixth International Conference on Acid Rock Drainage, 14-17 July 2003, Cairns, Queensland, The Australian Institute of Mining and Metallurgy Publication Series No 3/2003. The Australian Institute of Mining and Metallurgy, Carlton Victoria.*
- Lu, M. 2004. Pit lakes from sulphide ore mining, geochemical and limnological characterization before treatment, after liming and sewage sludge treatment. PhD-thesis, Lulea University of Technology, Lulea, Sweden.
- Lu, M., E. Carlsson and B. Öhlander 2003. Limnological and geochemical comparisons of two sulphide mine pit lakes. p. 201-212. *In: Tailings and Mine Waste '03. Swets & Zeitlinger, Lisse.*
- Lyons, W.B., G.A. Doyle, R.C. Petersen and E.E. Swanson 1994. The limnology of future pit lakes in Nevada: The importance of shape. p. 245-248. *In: Tailings and Mine Waste '94. Balkema, Rotterdam.*
- Madison J. P., Gammons C. H., Poulson S. R. and Jonas J. P. (2003) Oxidation of pyrite by ferric iron in the acidic Berkeley pit lake, Montana, USA. p. 1073-1078. *In: Farrell, T. and G. Taylor (eds.): Sixth International Conference on Acid Rock Drainage, 14-17 July 2003,*

- Cairs, Queensland, The Australian Institute of Mining and Metallurgy Publication Series No 3/2003. The Australian Institute of Mining and Metallurgy, Carlton Victoria.
- Maiss, H., V. Walz, M. Zimmermann, J. Ilmberger, W. Kinzelbach and W. Glässer 1998. Experimentelle Tracerstudien und Modellierungen von Austauschprozessen in einem meromiktischen Restsee (Hufeisensee). UFZ-Bericht 1/1998. UFZ-Umweltforschungszentrum Leipzig-Halle GmbH, Leipzig.
- Merilainen, J. 1970. On the limnology of the meromictic Lake Valkiajarvi, in the Finnish Lake District. *Ann. Bot. Fenn.* 7, 29-51.
- Miller, G.C., W.B. Lyons and A. Davis 1996. Understanding the water quality of pit lakes. *Environ. Sci. Techn.* 30, 118A-123A.
- Muggli, D.L., C.A. Pelletier, G.W. Poling and E.C. Schwamberger 2000. Injected ARD plume behaviour in a pit lake utilizing *in situ dye* studies. p. 305-318. *In: Proceedings Fifth International Conference on Acid Rock Drainage. Society of Mining, Metallurgy, and Exploration (SME), Littelton.*
- Murphy, W.M. 1997. Are pit lakes susceptible to limnic eruptions. p. 543-547. *In: Tailings and Mine Waste '97. Balkema, Rotterdam.*
- Nixdorf, B., M. Hemm, A. Schlundt, M. Kapfer and H. Krumbeck 2001. Braunkohlentagebauseen in Deutschland. UBA-Texte 35/01. Umweltbundesamt, Berlin.
- Parshley, J.V. and R.J. Bowell 2003. The limnology of the Summer Camp pit lake: A case study. *Mine Water and the Environment* 22, 170-186.
- Pellicori, D.A., C.H. Gammons and S.R. Poulson 2005. Geochemistry and stable isotope composition of the Berkeley pit lake and surrounding mine waters, Butte, Montana. *Appl. Geochem.* 20, 2116-2137.
- Poling, G.W., C.A. Pelletier, D. Muggli, J. Gerits, C. Hanks and K. Black 2003. Field studies of semi-passive biogeochemical treatment of acid rock drainage at the Island Copper Mine pit lake. p. 549-558. *In: Farrell, T. and G. Taylor (eds.): Sixth International Conference on Acid Rock Drainage, 14-17 July 2003, Cairns, Queensland, The Australian Institute of Mining and Metallurgy Publication Series No 3/2003. The Australian Institute of Mining and Metallurgy, Carlton Victoria.*
- Robins, R.G., R.B. Berg, D.K. Dysinger, T.E. Duaiame, J.J. Metesh, F.E. Diebold, L.G. Twidwell, G.G. Mitman, W.H. Chatham, H.H. Huang and C.A. Young 1997. Chemical, physical and biological interaction at the Berkeley Pit, Butte, Montana. p. 529-541. *In: Tailings and Mine Waste '97. Balkema, Rotterdam.*
- Rodrigo, M.A., M.R. Miracle and E. Vicente 2001. The meromictic Lake La Cruz (Central Spain). Patterns of stratification. *Aquat. Sci.* 63, 406-416.
- Rytuba, J.J., D. Enderlin, R. Ashley, R. Seal and M.P. Hunerlach 2000. Evolution of the McLaughlin Gold Mine pit lakes, California. p. 367-375. *In: Proceedings Fifth International Conference on Acid Rock Drainage. Society of Mining, Metallurgy, and Exploration (SME), Littelton.*

- Rücker, J., A. Fyson, R. Deneke, and G. Packroff 1999: Meromiktische Seen mit saurem Mixolimnion - eine Besonderheit der Lausitzer Bergbaufolgelandschaft. p. 239-243. *In: DGL-Tagungsbericht 1998 (Klagenfurt)*. Eigenverlag der DGL, Tutzing.
- Sanderson, B., K. Perry and T. Pedersen 1986. Vertical diffusion in meromictic Powell Lake, British Columbia. *J. Geophys. Res.* 91(C6), 7647-7655.
- Scharf, B.W. and M. Oehms 1992. Physical and chemical characteristics. *Arch. Hydrobiol. Beih.* 38, 63-83.
- Schimmele, M. 1999. Ausbildung von Meromixie durch physikalische und chemische Einflüsse am Beispiel von Bergbauseen. p. 234-238. *In: DGL-Tagungsbericht 1998 (Klagenfurt)*. Eigenverlag der DGL, Tutzing, Germany.
- Schreck, P. 1998. Environmental impact of uncontrolled waste disposal in mining and industrial areas in Central Germany. *Environ. Geol.* 35, 66-72.
- Schultze, M., B. Boehrer, A. Duffek, P. Herzsprung and W. Geller 2005. Introduction of river water as a tool to manage water quality in pit lakes. p. 273-279. *In: J. Loredó and F. Pendas (eds.)*. Proc. 9th International Mine Water Association Congress (Oviedo, Spain, September 5-7, 2005), Dept. Explotacion y Prospeccion de Minas, Univ. of Oviedo on behalf of the Intern. Mine Water Association, Oviedo, Spain.
- Stellmacher 2004. Der Moritzteich bei Döbern - Analogon für die Sanierung saurer Bergbaugewässer? Hydro- und Sedimentgeochemie eines meromiktischen Restsees. Masterthesis, Technical University Bergakademie Freiberg, Germany.
- Stevens, C.L. and G.A. Lawrence 1997. The effect of sub-aqueous disposal of mine tailings in standing waters. *J. hydraul. Res.* 35, 147-159.
- Stevens, C.L. and G.A. Lawrence 1998. Stability and meromixis in a water-filled mine pit. *Limnol. Oceanogr.* 43, 946-954.
- Stevens, C.L., T.S.R. Fisher and G.A. Lawrence 2005. Turbulent layering beneath the pycnocline in a strongly stratified pit lake. *Limnol. Oceanogr.* 50, 197-206.
- Stottmeister, U., A. Mudroch, C. Kennedy, Z. Matiova, J. Sanecki, and I. Svoboda 2002. Reclamation and regeneration of landscapes after brown coal opencast mining in six different countries. p. 4-36. *In: A. Mudroch, U. Stottmeister, C. Kennedy, and H. Klapper (eds.)*. Remediation of abandoned surface coal mining sites. Springer, New York.
- Stottmeister, U., W. Glässer, H. Klapper, E. Weissbrodt, B. Eccarius, C. Kennedy, M. Schultze, K. Wendt-Pothhoff, R. Frömmichen, P. Schreck and G. Strauch 1999. Strategies for remediation of former opencast mining areas in eastern Germany. p. 263-296. *In: Azcue, J.M. (ed.)*: Environmental impacts of mining activities. Springer, New York.
- Strøm, K. 1963. Trapped sea water. *New Scientist* 274, 384-386.
- von Rohden, C. and J. Ilmberger 2001. Tracer experiment with sulfur hexafluoride to quantify the vertical transport in a meromictic pit lake. *Aquatic Sciences* 63, 417-431.
- Walker, K.F. and G.E. Likens 1975. Meromixis and a reconsidered typology of lake circulation patterns. *Verh. Intern. Verein. Limnol.* 19, 442-458.

Younger,P. 2005. Westfield pit lake, Fife (Scotland): the evolution and current hydrogeological dynamic of Europe's largest bituminous coal pit lake. p. 281-287. *In*: J. Loredó and F. Pendas (eds.). Proc. 9th International Mine Water Association Congress (Oviedo, Spain, September 5-7, 2005), Dept. Explotación y Prospección de Minas, Univ. of Oviedo on behalf of the Intern. Mine Water Association, Oviedo, Spain.