On the relevance of meromixis in pit lakes – an update

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Abstract

The term “meromixis” means that a lake contains a chemically different, deep water layer due to incomplete mixing over the year. Ten years ago, Boehrer and Schultze (2006) discussed the relevance of meromixis for pit lakes. More than 100 papers have been published on meromixis in pit lakes since 2006, suggesting an update.

Newly published papers have dealt with the interaction of underground workings and ground-water within meromictic pit lakes, double diffusion and erosion of the chemocline, climatic influences on meromixis, biogeochemical processes and microbial ecology in the water column and sediments, and predictive modelling. Results of the monitoring of meromictic pit lakes improved the understanding of processes and allowed in some cases to prove results of earlier modeling. Experiences with the management of meromictic pit lakes were also published.

Meromixis is not the common mixing regime in pit lakes. However, meromixis seems to occur more frequently in pit lakes than in natural lakes due to the shape of the basin of pit lakes and the occurrence of chemically different waters in the catchment of many pit lakes. Therefore, and because of the particular chances and risks related to meromixis, it is of particular relevance in pit lakes. Based on the findings of the last ten years, predictive modeling of future pit lakes and the management of existing meromictic pit lakes can be made much better today.

This contribution gives a brief introduction to the phenomenon of meromixis in pit lakes, summarizes the findings from the last ten years and draws conclusions regarding the management and predictive modeling of meromixis in pit lakes.

Key words: pit lake, meromixis, management, modeling

Introduction

Findenegg (1935) introduced the term ‘meromictic’ into limnology in order to name lakes which do not experience a full overturn, and where the deep part of the waterbody which is excluded from uverturn is chemically different from the regularly mixing upper part of the lake. The lower part of the lake was named the ‘monimolimnion’ by Findenegg (1935) while the upper part was named the ‘mixolimnion’ by Hutchinson (1937). Figure 1 shows a scheme of a meromictic lake and temperature, salinity and pH in Lake Goitsche (Germany), a pit lake in a former open cast lignite mine.

The incomplete mixing is caused by the density difference between mixolimnion and monimolimnion. Other factors like: (1) the shape of the lake basin, (2) sheltering from wind forcing at the lake surface (e.g. by steep side walls of a former mine void or by surrounding forest or montains), or (3) climatic conditions (e.g. formation of an ice cover) may also contribute to the formation and stability of meromixis. However, such factors are not able to cause the formation and stability of meromixis alone as some earlier literature suggested (e.g. Lyons et al. 1994; Doyle and Runnels 1997). Jöhnk (2001) demonstrated that ‘relative depth’, a geometric relationship between the surface area and maximum depth often used to quantify the shape of lake basins, is not a reliable predictor for meromixis.

The above mentioned difference in density between mixolimnion and monimolimnion needs to be sustained. There are several mechanisms that can sustain the density difference and also cause the formation of meromixis. According to Hutchinson (1937, 1957), these include: (1) inflow of saline surface water into a fresh water lake or fresh surface water into a saline lake, forming and stabilizing a fresher layer of water on top of a more saline and denser water layer at the lake bottom, named ‘ectogenic meromixis’, (2) inflow of saline groundwater into a lake, called ‘crenogenic meromixis’, and (3) liberation and enrichment of solutes in the deeper part of a lake mainly due to biological activity (e.g. decay of organic matter in the deep part of the water body or in the lake sediment), called ‘biogenic meromixis’. Walker and Likens (1975) distinguished two classes of meromixis based onthe mechanisms causing and stabilizing meromixis: ectogenic (i.e. developed from external mechanisms) and endogenic (i.e. developed from internal mechanisms). The first class encompases Huchison’s ectogenic and crenogenic meromixis while the second class comprises Hutchison’s biogenic meromixis plus meromixis caused by downward settling of precipitated minerals as well as sinking of salts excuded during ice formation.

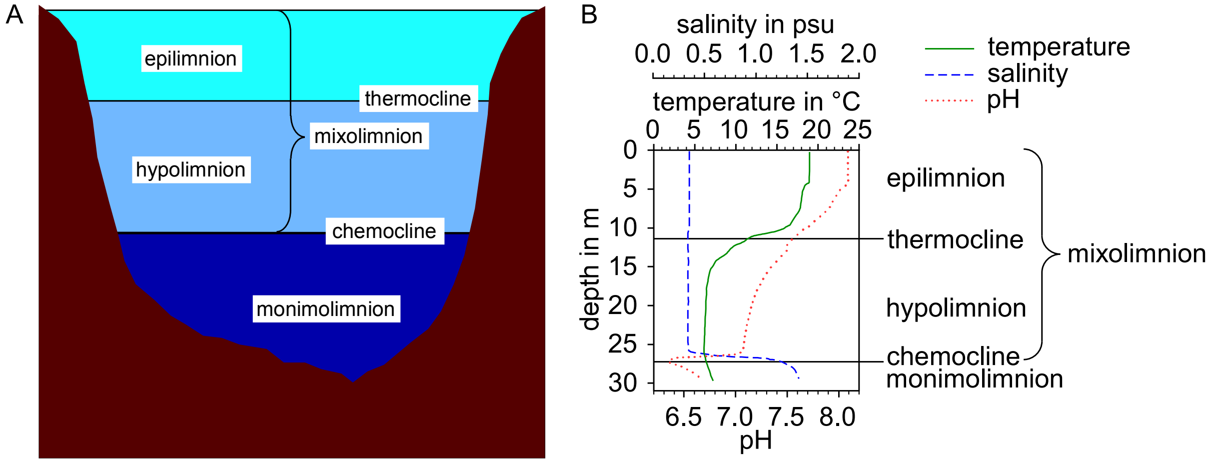

***Figure 1** Terminology of stratification in meromictic lakes (details see text): panel A - generalized cross-section through a meromictic lake (under conditions of temperate climate during summer, i.e. thermal stratification in the mixolimnion); panel B - profiles of temperature, salinity and pH in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

Publications of the last ten years (2006-2015)

Bibliographic analysis

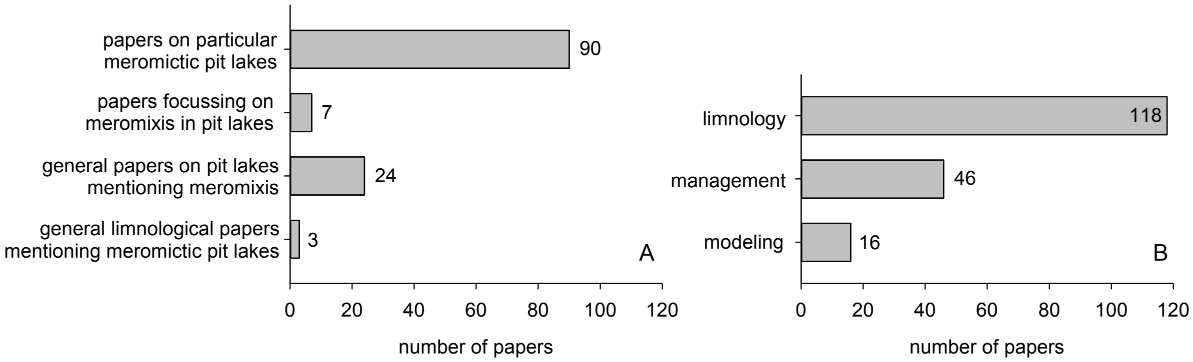

***Figure 2** Analysis of papers published on meromixis in pit lakes since 2006. Panel A: all papers are considered for one category only. Panel B: Papers may be considered for more than one category (limnology comprises physics, chemistry and biology).*

In order to get an overview of what has been published in the last ten years, we had a look into our collections of literature and also did a search using Google Scholar using the combined key words 'meromixis', 'meromictic', and 'pit lake'. Figure 2 shows a simple statistical evaluation of the outcome. We found 124 publications to be considered. They comprise conference papers, journal papers, book chapters and PhD theses. The majority (72.6%) reported findings from particular meromictic lakes. Some lakes have frequently been subject of research and publications: Cueva de la Mora (Spain), Waldsee (Germany) and Berkeley Pit Lake (USA). Only few publications (5.6%) have focused on meromixis in pit lakes while 19.4% of the publications generally dealt with pit lakes and mentioned meromixis. In three cases (2.4%), meromixis in pit lakes was mentioned in general limnological publications related to stratification in lakes.

Thematically, the majority of publications covered limnological aspects of meromictic pit lakes, i.e. physical, chemical and biological properties and processes of the pit lakes. However, management and modeling have also been important aspects. Regarding management of meromictic pit lakes, the Island Copper Mine pit lake is doubtless the most prominent example: no other meromictic pit lake has been reported that experiences such strong artificial control of creation, hydrology and biogeochemistry (Fisher and Lawrence 2006; Pelletier et al. 2009; Wen et al. 2015).

Limnology of meromictic pit lakes

In pit lakes, ectogenic and crenogenic origin of meromixis (sensu Hutchinson 1937, 1957) are by far dominant. Flite (2006) reported the rare case of biogenic meromixis in the filling pit lake of the former Kennecott Ridgeway Gold mine in South Carolina. He underlined the role of the basin shape in this case. Sánchez-España et al. (2009) also discussed the role of the basin shape. However, the actual contribution of the basin shape to the stability of meromixis was not quantified in either of these cases.

Mixing between the mixolimnion and the upper part of the chemocline ('erosion of the chemocline') is one of the processes which eventually may remove meromixis. Boehrer et al. (2014) quantified this effect based on long term observations in Lake Wallendorf (Germany). The importance of a good understanding of this process appeared in the Island Copper mine pit lake (Canada): The erosion of the chemocline was much smaller than predicted by the modeling before filling the lake (Pelletier et al. 2009). Therefore, the so-called "Middle-layer-lifting-system" had to be developed and implemented in the Island Copper mine pit lake. It transfers water from the monimolimnion to the mixolimnion in order to limit the rise of the chemocline which results from the injection of acid drainage into the monimolimnion for treatment and deposition (Pelletier et al. 2009). This approach is possible only because the renewal rate of the mixolimnion by inflow of fresh and slightly brackish water is fast enough to keep the density difference between mixolimnion and monimolimnion big enough.

A further example underlining the importance of mixolimnion renewal was presented by Santofimia et al. (2012). They observed a full overturn of the formerly meromictic pit lake Nuestra Señora del Carmen (Spain) as a consequence of the exceptionally late onset of rain in autumn. The evaporation during summer caused an increase in density in the mixolimnion eventually making the density difference between mixolimnion and monimolimnion too small. Early onset of rain in the following autumn re-established meromixis (Santofimia et al. 2012).

The importance of (in particular long lasting) ice covers for the stability of meromixis in pit lakes was investigated by Pieters and Lawrence (2009, 2014). Ice covers act in two ways: During freezing, salts are excluded from the ice. Therefore, melting ice forms a fresh water layer on top of the lake. Snow melt in the catchment of the pit lake may also contribute to this. In addition, the highly concentrated water forming immediately below the ice is moving downward due to its high density and contributes to accumulation of dissolved solids in the monimolimnion. The second effect of an ice cover is hindering of mixing at the chemocline by protecting the water body against wind forcing. A similar effect was observed by Boehrer et al. (2014). The filling of Lakes Wallendorf and Rassnitz (Germany) with river water created additional chemoclines on top of already existing meromictic water bodies and hindered erosion of the chemocline. Seasonal establishment of thermoclines in the mixolimnion also contributed to this effect.

Sánchez-España et al. (2009) and Santofimia et al. (2013) demonstrated the relation between abandoned underground workings and the layering in meromictic pit lakes in Spain (Cueva de la Mora, Concepción, respectively). Surprisingly, Sánchez-España et al (2014a) found by studying the isotopic composition of the water that the current exchange between the underground workings and the lake is very small. The underground workings were mainly important for the formation of meromixis during the filling of the lake (Sánchez-España et al. 2014a; Diez-Ercilla, 2015).

Double diffusion had been demonstrated to occur and to be important in meromictic pit lakes (Boehrer et al. 2009; von Rhoden et al. 2010; Sánchez-España et al. 2014a; Diez-Ercilla 2015). It is the formation of staircase-like profiles of temperature and concentrations in density stratified water bodies, which results from largely different diffusivities of dissolved substances and heat. In case of meromictic Lake Waldsee (Germany) double diffusion even caused a complete mixing within the monimolimnion (Boehrer et al. 2009).

Lake Waldsee was also the first meromictic pit lake where the contribution of the single constituents to the density difference between mixolimnion and monimolimnion was quantified (Dietz et al. 2012). In this case, iron and bicarbonate were most important (Dietz et al. 2012). The quantification was based on the calculation of water density using the partial molal volumes of the water constituents (Boehrer et al. 2010). This approach enables the identification of options for selective manipulation of the stability of meromixis by promotion or hindering of biogeochemical processes in the monimolimnion as part of the lake management.

The case of Guadiana pit lake in Herrerıás mine (Spain; Sánchez-España et al. 2014b) confirmed the expectations of Murphy (1997) that limnic eruptions (sudden uncontrolled release of high amounts of gas accumulated in the monimolimnion) are possible in pit lakes. In Guadiana pit lake, the concentration of CO_2 in the monimolimnion (as a result of water/rock interaction leading to carbonate dissolution) became high enough that there is a real risk of a limnic eruption, and measures for a controlled removal of the excess CO_2 were tested in the field (Boehrer et al. 2016).

In Cueva de la Mora (Spain), the mixolimnetic algal growth was found to be the main source for the reductive microbial processes occurring in the chemocline, monimolimnion and sediments (Wendt-Potthoff et al. 2012; Falagán et al. 2014). An interesting finding was that precipitation of copper and arsenic sulphides worked well as a natural attenuation mechanism while precipitation of iron sulphide was found only exceptionally and only at greater depth although ferrous iron was present in concentrations of >400 mg/L (Diez-Ercilla et al. 2014).

Pit lakes in former open cast sulphur mines are rare. There were several publications on a meromictic pit lake in a former sulphur mine within the period 2006-2015: Lake Piaseczno (Poland). Due to origin of the sulphur deposit from microbial transformation of gypsum to sulphur bearing limestone, the lake water is neutral. Most relevant for the density difference between mixolimnion and monimolimnion are sodium and chloride (Frankiewicz and Pucek 2006). For more details of chemistry, biology and sediments see Żurek and De Pauw (2006), Mazurkiewicz-Boroń et al. (2008), Szarek-Gwiazda (2008).

Management of meromictic pit lakes

In the Island Copper Mine pit lake, the basic applicability of the initial planning and modeling approaches was confirmed (Fisher and Lawrence 2006; Pelletier et al. 2009; Wen et al. 2015). However, some adaptations were needed. Application of fertilizer was found to be necessary year-round to ensure sufficient adsorption of trace metals to algae and their removal from the mixolimnion by sedimentation. Also, the above mentioned ‘Middle-layer-lifting-system’ had to be implemented. The management of the Island Copper Mine pit lake is a good example for adaptive management based on monitoring and additional field experiments (Pelletier et al. 2009, Wen et al. 2015).

The Anchor Hill pit lake (South Dakota, USA) turned meromictic due to a full scale test of a treatment approach for its acidic, metal and nitrate rich water (Park et al. 2009). After initially raising the pH from 3 to 5, a mixture of molasses, methanol and proprietary ingredients was added as nutrient for anaerobic bacteria. Following a re-adjustment of pH to 6, wood chips were added as substrate for bacterial growth. Nitrate and sulphate reduction worked well and the metals were precipitated as sulphides. In order to remove excess hydrogen sulphide and to meet discharge criteria for the treated water, hydrogen peroxide was finally added (Park et al. 2009). Since discharge criteria were met, this is a successful new approach for treating acid mine drainage in a batch process, using the monimolimnion as a biochemical reactor.

The Berkeley pit lake had long been known to be meromictic (Davis and Ashenberg 1989). However, there was a period of holomixis caused by a land slide, which was terminated by diverting more fresh water to the lake (Gammons and Tucci 2013). Later on, the ex-situ recovery of copper from monimolimnetic water and the release of the treated water into the mixolimnion made the lake holomictic again (Gammons and Tucci 2013; Tucci and Gammons 2015). Although terminating meromixis may not have been fully intended, this experience is very instructive and valuable because it is well documented and published. Others can learn and benefit from this development: when increasing the density of the mixolimnion by addition of treated monimolimnetic water, the density difference between mixolimnion and monimolimnion becomes gradually smaller and mixing between both layers increases. Furthermore, permanent extraction of monimolimnetic water eventually removes the monimolimnion.

A clearl case of intended meromixis cessation is the Zone 2 Pit Lake at Colomac mine site (Canada; Pieters et al. 2015). Here, artificial destratification known from the abatement of anoxia in eutrophic lakes (Cooke et al. 2005) was applied to improve lake water quality. The main goal was to enhance microbial conversion of thiocyanate and ammonia resulting from cyanide gold mining. The approach fully succeeded (Pieters et al. 2015).

Long term observations at Lake Vollert Süd (Germany) demonstrated that the storage of contaminants in the monimolimnion has so far been successful (Stottmeister et al. 2010; Wiessner et al. 2014). In this case, mainly phenolic wastes from lignite gasification and coke production were removed from the mixolimnion by flocculation. This allowed for the development of common plankton in the lake and for oxidation of remaining organic compounds and ammonia in the mixolimnion (Stottmeister et al. 2010; Wiessner et al. 2014).

Modeling of meromictic pit lakes

Only few models of meromictic pit lakes could be tested by real data since the models were often used for predictions in the course of planning mine closure. For the Island Copper Mine pit lake (Canada), predictive modeling was basically successful although some of the predictions were not fully met by reality (see above sections). The prediction of Boehrer et al. (1998) for Lakes Wallendorf and Rassnitz (Germany) were also accurate (Schultze and Boehrer 2008; Boehrer et al. 2014). The modeling of Lake Waldsee (Germany) by Moreira et al. (2011) underlined the importance to include biogeochemical processes into the modeling of meromictic pit lakes. While Moreira et al. (2011) coupled a hydrodynamic and a geochemical model, Castendyk and Webster Brown (2007a,b) did the predictive modeling of the future lake in Marta Mine (New Zealand) separately for hydrodynamics and geochemistry. Predictive modeling of the future lake in Aitik Mine (Sweden) by Fraser et al. (2012) demonstrated the importance of the sequence of the use of chemically different water sources for lake filling which was found to be decisive for the formation of meromixis.

Making use of investigations from existing meromictic pit lakes for improving the reliability of predictions for future pit lakes is a very valuable strategy (see Mueller et al., 2012). The very long perspective of the predictive modeling for future pit lakes in De Beers' Gahcho Kué Mine (Canada; Herrell et al. 2015; Vandenberg et al. 2016) is rather exceptional. These studies demonstrate both the need of such long term predictions and also the uncertainties caused by the potential change of the hydrological conditions in a period of about thousand years. The climate has already changed considerably in the last thousand years at times when the anthropogenic influence was much smaller than in recent years, e.g. during medieval climate anomaly and little ice age (e.g. Mann et al. 2009). Further anthropogenic climate change could significantly affect the accuracy of contemporary pit lake predictions which frequently assume consistent climate and water balance conditions in the future.

Conclusions

As shown by the reviewed literature, successful active management of meromictic pit lakes is possible. It requires a comprehensive understanding of all relevant processes in the pit lakes. Models are key instruments for planning meromictic pit lakes and also the management strategy. Adequate monitoring, the critical evaluation of its results, and a regular updating of management strategies are indispensable for the successful management of meromictic pit lakes.

The findings of the last ten years underlined that biogeochemical processes have to be included into modeling of meromictic pit lakes. In order to validate and improve models, more monitoring results have to be published from existing meromictic pit lakes. This is not only a scientific need but also of interest for mining companies and authorities. Improved models well-tested, using published data would minimize the re-creation of past errors, maximize the knowledge gained from past experience, reduce the remaining risks during decision making, and increase public acceptance of decisions. From a more scientific point of view, a systematic and comprehensive model study on the influence of lake basin shape on formation and stability of meromixis is desirable. However, funding such project would also result in benefit for industry and authorities via improvement of the basis of predictive modeling, one of the key instruments of planning open cast mines and their closure. This could become an excellent example of enhancing mining industry and academic collaboration (McCullough 2016).

We assume that we did not find all publications on meromixis in pit lakes from the last ten years. Therefore, we would be grateful to receive references for overlooked publications. A list of publications found by the authors will be made available at the web page of Martin Schultze and updated yearly. There are likely to be interesting case studies of meromictic pit lakes, and valuable experiences not available to the mine water community and the public yet. We would like to encourage the owners, the consultants, and the authorities to be less hesitant in publishing their results and experiences for the mutual benefit of all.

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