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Chemocline erosion and its conservation by freshwater introduction to meromictic salt lakes

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ABSTRACT

Salinity stratification has been documented in two meromictic lakes in detail. We present seven years of field data on the salinity stratification of meromictic lakes Wallendorfer See and Rassnitzer See forming in the pits of the former lignite mine Merseburg-Ost in the Central German Mining District. Mainly from groundwater inflows, salinity stratified meromictic residual lakes had formed before freshwater was introduced intentionally over a period of two years to fill the pits more rapidly close to the final water level. From the observations, changes in the salinity stratification were interpreted in terms of deposited potential energy. Freshwater introduction (capping) was quantified in terms of potential energy. Thus the evolution of the salinity profiles was explained and their residual shapes became understandable as a consequence of the flooding procedure. Based on the quantitative estimates of energy deposited in the stratification during deep recirculation in winter, prospective statements could be made about the further evolution of the monimolimnia.

Introduction

Although about half of all lakes are salt lakes, they have attracted much less scientific interest than their freshwater counter parts (Williams, 1996). However, with increasing demand for water within the next years and decades, be it from population growth world-wide or from increased living standards and requirements, salt lakes may be considered as a source of water, when technical facilities are available to improve water quality.

In lakes, pronounced chemical gradients can form, if vertical circulation is incomplete over the annual cycle. Such lakes are called meromictic, if they show such pronounced chemical gradients throughout the year. Meromixis has been known to limnologists for decades (Findenegg, 1935; Hutchinson, 1957) and implications for the biology and chemistry of the lakes have been studied (e.g. Camacho et al., 2001; Hamersley et al., 2009; Degermendzhy et al., 2010). It is assumed that changing climate conditions will impact the circulation patterns of lakes. The incomplete circulation over the annual cycle impacts on the distribution of nutrients and the provision of oxygen to deeper layers. Hence the establishing community of organisms is directly affected, with all positive and negative aspects of recycling matter from the sediments and bioturbation, or the presence of varves and their usability for paleo studies.

Implications of salinity stratification on the circulation pattern and thus on the chemistry and biology of the surface waters will be of central interest. Additionally in many regions of the world, mining lakes are increasingly becoming a common feature of landscape disruption (e.g. Lyons et al., 1994; Miller et al., 1996; Klapper and Geller, 2001; Nixdorf et al., 2001; Stottmeister et al., 2002; McCullough, 2008; Castendyk and Eary, 2009b; Geller et al., 2013a,b). Mining lakes are believed to be particularly prone to meromixis (e.g. Lyons et al., 1994; Miller et al., 1996; Sanchez-Espana et al., 2009; Boehrer and Schultze, 2008). Lake sizes in general lie in the range of 100 m to 10 km in the horizontal. The depth may reach beyond 50 m in the Central German mining region (Schultze et al. 2010) or even more than 300 m in former metal mines (e.g. Fisher and Lawrence, 2006; Gammons and Tucci, 2013). As a considerable fraction of these lakes lies within densely populated areas, public pressure is high to make these lakes suitable for public use. They should not interfere negatively with the established social and ecological environment. To employ remediation techniques (e.g. Klapper and Schultze, 1995; Stottmeister et al., 1999; Castro and Moore, 2000; Koschorreck et al., 2002; Castendyk and Eary, 2009a; Stottmeister et al., 2010; Geller et al., 2013b) and to predict their sustainability, e.g. the leakage of undesirable substances out of the monimolimnion, quantitative knowledge of transport processes in salinity stratified lakes is essential (see also Stevens and Lawrence, 1997; Boehrer, 2000; Fisher and Lawrence, 2006; Gammons and Tucci, 2013).

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Various processes can create or sustain meromixis (Strøm, 1945; Kjensmo, 1967, 1968; Boehrer and Schultze, 2008). Vertical transport in stratified deep waters of lakes (e.g. Hamblin et al., 1999; Boehrer et al., 2000) – especially when density gradients are large – has been investigated and quantified in only few cases (Sanderson et al., 1986; von Rohden and Ilmberger, 2001; Schmid et al., 2004). Though vertical transports are small, monimolimnia are not entirely excluded from vertical exchange. Based on Helium dating, Aeschbach-Hertig et al. (1999) estimated the age of monimolimnetic waters in Lac Pavin, France to 70 years. As a consequence of missing knowledge about transports out of monimolimnia, still nowadays a reliable numerical modelling of a meromictic lake remains a challenge (Stevens and Lawrence, 1997, 1998; Jellison et al., 1998; Böhrer et al., 1998; Castendyk and Webster-Brown, 2007a,b; Moreira et al., 2011).

Introduction of freshwater to a saline lake can affect its circulation pattern. Already Jellison and Melack (1993) pointed out that Mono Lake turned meromictic due to higher inflows, and correlated the meromictic phase (1983–1988) with the water level. Similar was seen in Lake Van, Turkey by Kaden et al. (2010). Jellison and Melack (1993) also pointed out that both onset and breakdown of meromixis impacted on nutrient fluxes and the ecology of the entire lake. Romero and Melack (1996) showed in a numerical study that higher freshwater inflows to Mono Lake raised the probability for meromixis (see also MacIntyre and Jellison, 2001). After turning meromictic in 1997 due to higher freshwater inflows, Mono Lake was holomictic again from 2003 on. Santofimia et al. (2012) demonstrated the essential role of annual recharge with freshwater in sustaining meromixis in the Spanish pit lake Nuestra Senora del Carmen. von Rohden et al. (2009) presented observational data of a chemocline oscillating seasonally as a result of groundwater inflow and convective erosion.

Though the connection between freshwater introduction and reduced recirculation depth has been documented in several occasions, the presented investigation is the first to display sufficient data for a straight quantitative approach for the reduced recirculation depth and the omission of winterly erosion of the monimolimnion. We first produce a quantitative estimate for the deposited potential energy in the salinity stratification. Referring to data from both lakes in the pits of Merseburg-Ost, we quantified the annual erosion of the monimolimnia in three deep depressions of the lake basins. We also evaluated the sheltering effect by introducing freshwater over the flooding period quantitatively. It became clear how the introduced freshwater could protect the monimolimnia from the wind impact. Comparison of both numbers demonstrated in which years chemocline erosion could happen, which was the key to understanding the shape of the residual salinity profiles in the permanently stratified deep waters of both lakes.

Potential energy considerations

We considered the case where a mixolimnion of thickness h and salinity S_1 was floating on top of a monimolimnion of salinity S_2 (Fig. 1). The density difference between mixolimnion water and monimolimnion water was due to the salinity gradient and could be estimated by $\Delta\rho = \gamma\Delta S = \gamma(S_2 - S_1)$, where $\gamma = 0.77\,\mathrm{kg/(m^3\,psu)}$ was derived as the incremental density contribution of salinity at temperature 15 °C, atmospheric pressure and salinity of 10 psu from the UNESCO formula (Fofonoff and Millard, 1983). As most of the mixing was taking place when thermal stratification did not play the leading role, we did not include thermal stratification. Within a period of t, a layer of thickness Δz was shaved off the monimolimnion and mixed into the mixolimnion. We quantified this monimolimnion erosion by the energy per unit area that was required to facilitate this process.

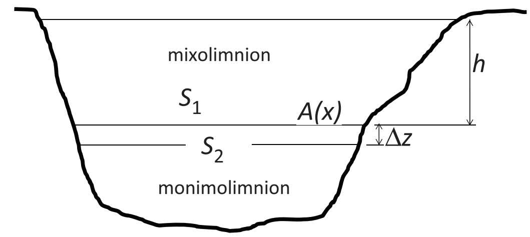

Fig. 1. Sketch of a salinity stratified lake, with an mixolimnion of salinity S_1 lying over a monimolimnion of salinity S_2.

The volume of the shaving was $V = A(z)\Delta z$. This volume was distributed about the entire volume of the mixolimnion. The denser water had to be lifted against gravity $g = 9.81\,\mathrm{m/s^2}$. Potential energy is gained, which must be delivered from some source. In a cylindrical lake, i.e. $A(z) = \text{const.}$, the average distance of vertical lift amounts to $z_{avg} = h/2$. As the cross section $A(z)$ increases towards the surface of a real lake, the average lift z_{avg} lies closer to h. Apparently smaller values than $z_{avg} = h/2$ would require a widening of the basin to greater depths, which is hardly possible. In fact, a more realistic lake basin of the shape of a cone or a pyramid, has a $z_{avg} = h/2$, when the chemocline approaches the surface (nearly constant cross sections) and a value of $z_{avg} = 3h/4$ for the chemocline approaching the deepest point. z_{avg} has its maximum when the chemocline reaches the deepest point as cross section is the smallest. For any arbitrary shape of lake basin, the last droplet at the deepest point is lifted by the maximum depth and lowered by half the average depth, when distributed over the entire lake volume $z_{avg}(z = -H_{\max}) = H_{\max} - H_{avg}/2 = 1 - H_{avg}/2H_{\max}$. Hence this upper limit for z_{avg} can be calculated from maximum and average depths of 60 Alpine lakes in Herschy's (2013) list. All values lie between 0.66 and 0.8. In conclusion, the average lift does not vary very much between basin shapes and cones or pyramids are good average references.

Using $z_{avg} = h\cdot(5/8 \pm 1/8)$ spans from the minimum to the maximum of the cone-shaped basin, and there is good reason to believe that most lacustrine conditions are covered with this approximation. This means vertical lift is known within an accuracy of about 20%. For any more accurate value, considerable morphometric data on the lake basins would be required. We however feel that such an effort and the resulting complexity would not be justified due to other sources of inaccuracy. In conclusion, the erosion was noted as the work E_{sal} done in the time period t per unit area A:

$$P_{sal} = \frac{E_{sal}}{At} = \frac{g\Delta\rho V z_{avg}}{At} = \frac{5g\Delta\rho Vh}{8At} = \frac{5g\gamma\Delta SVh}{8At} = \frac{5g\gamma\Delta S\Delta zh}{8t} \quad (1)$$

Study site and measurements

In this contribution, we refer to two neighbouring lakes (Wallendorfer See and Rassnitzer See) forming in the pits 1a and 1b in the Central German lignite mining complex Merseburg-Ost, in the outskirts of Leipzig about 140 km southwest of Berlin (Fig. 2). The major environmental concern connected with the pits was the high salinity of their waters, especially as only 8 km west of the pit 1a, groundwater was withdrawn for drinking water supply. Besides the salinity effect on the community of organisms in the lake (e.g. Zippel and Schimmele, 1999), inhabitants of the area feared that water quality could deteriorate and local flora and fauna could suffer from saline waters possibly entering the upper aquifer and local streams. As a consequence, a survey for the evolution of lake water quality was employed. Predictions for the future salinity profiles in