Chapter 2
Physical Features of Meromictic Lakes: Stratification and Circulation

Bertram Boehrer, Christoph von Rohden, and Martin Schultze

2.1 General Features

In meromictic lakes, a chemically different deepwater layer "the monimolimnion" remains perennially as a consequence of insufficient mixing with the overlying water body "the mixolimnion" (e.g., Findenegg 1933, 1935, 1937; Hutchinson 1937, 1957; Boehrer and Schultze 2008).

The transition between *mixolimnion* above and *monimolimnion* below is called the *chemocline*, as many chemical conditions change over a short vertical distance (Hutchinson 1957). Usually higher concentrations of solutes in the monimolimnion and stable density stratification are sustained throughout the annual cycle. In most cases, a high density gradient restricts the vertical exchange of water parcels and hence the turbulent transport of dissolved substances as well as heat. As a consequence, strong chemical gradients are conserved, and a fine zonation in this depth range can establish. Scientists looking at different features of the chemocline (gradients of electrical conductivity, oxygen, organisms, etc.) refer to slightly different depth ranges within this zone when speaking of "chemocline" (see Fig. 2.1).

The mixolimnion shows stratification and circulation patterns as in holomictic lakes, i.e., lakes without a monimolimnion, with the usual vertical subdivision into epilimnion (upper layer) and hypolimnion (lower layer). At the end of the thermal stratification period, deep recirculation mixes both layers. A lake (or the

B. Boehrer (✉) • M. Schultze
Department Lake Research, UFZ Helmholtz Centre for Environmental Research, Magdeburg, Germany
e-mail: bertram.boehrer@ufz.de

C. von Rohden
Institute For Environmental Physics, University of Heidelberg, Heidelberg, Germany

Lindenberg Meteorological Observatory, German Weather Service, Lindenberg, Germany

© Springer International Publishing AG 2017
R.D. Gulati et al. (eds.), *Ecology of Meromictic Lakes*, Ecological Studies 228,
DOI 10.1007/978-3-319-49143-1_2

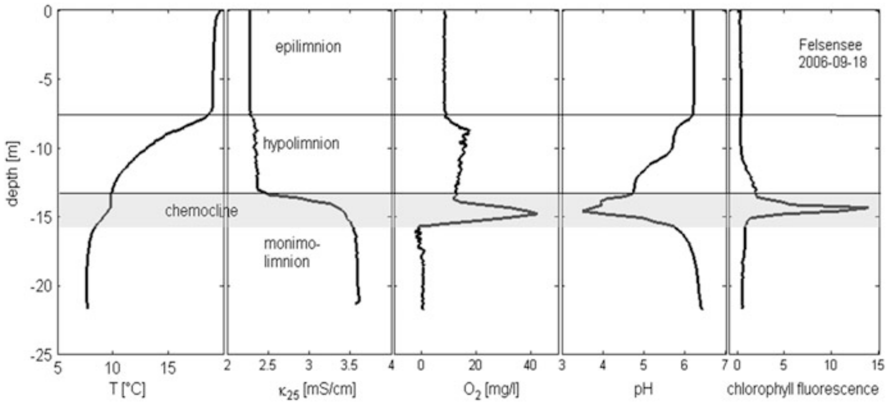

Fig. 2.1 Profiles of temperature, electrical conductance, oxygen concentration (numerically corrected for sensor response time), pH and fluorescence of the chlorophyll against depth in Felsensee (near Magdeburg, Germany). The *upper horizontal line* indicates the interface between epilimnion and hypolimnion, while the *lower horizontal line* marks the interface between hypolimnion and chemocline

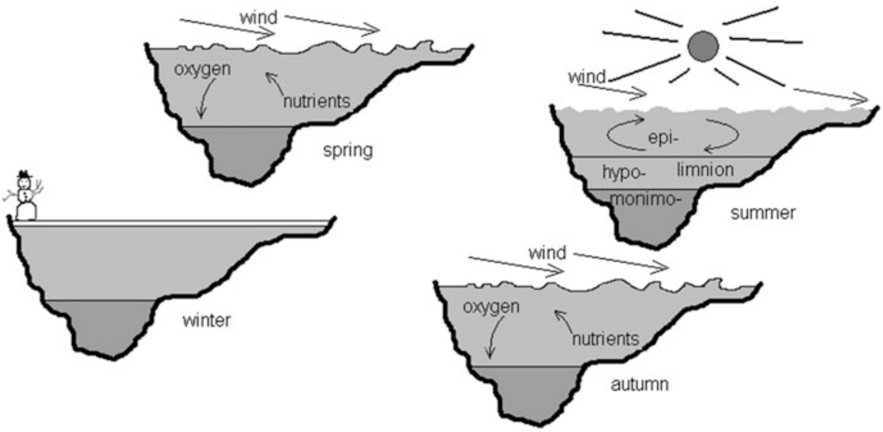

Fig. 2.2 Sketch of stratification and recirculation in a meromictic lake over an annual cycle

mixolimnion of a meromictic lake) can be monomictic (one recirculation period during the cold season) or dimictic (with a deep recirculation during spring and autumn—see Wetzel 2001—over an annual cycle depending on the climate zone; Fig. 2.2).

Similar to deeper holomictic lakes, a water layer at the surface heats up in spring as a consequence of increased solar irradiation and contact to a warming atmosphere. As a consequence, warmer water is formed, which floats on colder, denser water. While the upper layer, the epilimnion, is exposed to gas exchange and energy transfer with the atmosphere all year round, the hypolimnion below is shielded from direct impact during summer. Usually the hypolimnion remains density stratified over the summer stratification period. Hence, vertical exchange of water parcels requires energy, which is available only in a limited amount. As a consequence, vertical transport of solutes and heat is small during stratification periods.

Over the summer stratification in the mixolimnion, little is happening about the depth of the chemocline. Groundwater may enter the monimolimnion and contribute to its volume, and hence the chemocline slowly rises (von Rohden et al. 2010). In addition, diffusion and turbulent transport of solutes from the monimolimnion can raise the density gradient locally and lead to oxygen demand in the lowest zone of the hypolimnion. Affected water may change its properties from hypolimnetic to monimolimnetic and eventually become a part of the monimolimnion. An ice cover can add another period of quiet conditions (winter stagnation). In latitudes where ice cover extends for a long period, this can result in meromixis (e.g., lakes Shira and Shunet, Chap. 6), as the subsequent circulation in spring time is short or is completely missing. The ice cover together with the quick warming up due to high concentrations of colored humic substances (Eloranta 1999), basin shape, and an almost complete protection from wind probably cause high frequency of meromixis in the small, humus-rich forest lakes in Finland (Merilainen 1970; Salonen et al. 1984).

Later in the year, cooling at the lake surface removes the protecting thermal density stratification, and convection forces water motion down to the chemocline. Turbulent kinetic energy is used to shave off parts of the chemocline. As a consequence, the chemocline moves downward and gradients get sharper. The upper part of the monimolimnion gets included in the mixolimnion and so do the water and chemicals contained in it. This is of particular interest for nutrients available at higher concentrations in the monimolimnion. The volume of water introduced into the mixolimnion depends on weather conditions during the recirculation periods and may, therefore, greatly vary from year to year. The deeper monimolimnion remains unchanged as long as its density is greater than that of the mixolimnion and it is sufficient to withstand the erosion by advected and locally produced turbulent kinetic energy.

Typically meromictic lakes show increasing electrical conductance with depth because of increasing concentrations of ionic solutes with depth. In general, higher concentrations of solutes increase the density of water (see below paragraphs on density). Due to mixing at least once each year, differences between epilimnion and hypolimnion are small. However, gradients between mixolimnion and monimolimnion can be enormous. Gradients are known to range from salinity under freshwater conditions to salt concentrations exceeding beyond salinity in ocean water (Wallendorfer See, Germany; Boehrer et al. 2014) or exceeding 100 g/L as in hypersaline meromictic lakes (e.g., Hot Lake, USA; Zachara et al. 2016; see also Chap. 3).

Temperatures at the lake surface are determined by weather conditions, while in the hypolimnion, one usually finds temperatures prevailing during the last cold period (e.g., Boehrer et al. 2000). In lakes located in colder climates, hypolimnion temperatures are close to the temperature of maximum density under normal conditions (i.e., 4 °C for freshwaters but slightly lower at high salinities). Interestingly the monimolimnion is locked between hypolimnion above and ground/groundwater below. While its upper boundary is defined by temperatures during the cold period of the year, the lower boundary is warmer due to groundwater reflecting more an annual average temperature and geothermal heat flux. Usually a monimolimnion has a temperature gradient that reduces the density gradient imposed by dissolved substances.

Both, the permanent density stratification in the deep water and the seasonal circulation of the mixolimnion, determine the distribution of solutes, as we show for oxygen as one of the key solutes for organisms. At the water surface, the atmosphere implies the boundary condition for oxygen. As a consequence, the epilimnion usually shows oxygen concentrations close to the equilibrium with the atmosphere, i.e., close to 100 % saturation (by definition) at the respective temperature. The hypolimnion can have higher concentrations of oxygen than the epilimnion due to higher solubility of oxygen at lower temperatures during the last mixing period or due to photosynthesis, if the light penetrates to deeper layers. However, over the stratification period, oxygen in the hypolimnion is subject to depletion until the next circulation period when the oxygen levels are recharged. Oxygen concentrations drop to zero across the chemocline. The extent of availability of oxygen sets the conditions for the fate of other solutes. As the contact line between water masses of different chemistry, the chemocline is a zone of active chemical transformations (see Fig. 2.3). Consequently, organisms have to cope with the chemical conditions in this gradient zone. Some organisms manage to profit from unusual chemical conditions (see Chap. 4).

2.2 Processes Forming Meromixis

In general, water density is higher in the monimolimnion than in the mixolimnion so as to retain the monimolimnion throughout the year. To balance the gradual reduction of this density difference by diffusion and mixing, a process is required that transports substances into the higher concentration waters of the monimolimnion.

Hutchinson (1957) classified meromictic lakes according to the major processes that transport solutes. He could identify three classes, (1) ectogenic, (2) crenogenic, and (3) biogenic meromixis, i.e., meromixis caused by (1) external inflows, (2) groundwater, or (3) degradation of organic material, respectively. On a broader base of examples, Walker and Likens (1975) refined Hutchinson's classification into groups when lakes remain permanently stratified due to (1) inflows of different salinity, (2) inflows of high turbidity, or (3) inflowing groundwater. These three groups comprise ectogenically meromictic lakes (class A), while endogenic meromixis (class B) is formed either by (4) degradation of organic material in the deep water or (5) by salt exclusion when ice is formed during winter.

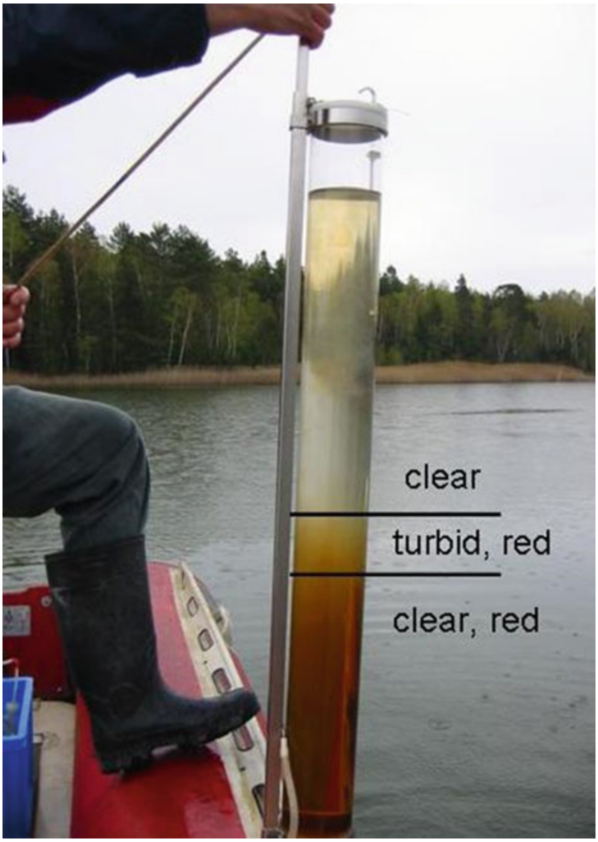

Fig. 2.3 Water sample from about 10 m depth from Moritzteich (south of Berlin, Germany), showing the transition from colorless water of mixolimnion (*upper* part of the sampling tube) to red water of monimolimnion (from Boehrer 2013). The turbidity in the chemocline is the result of oxidation and precipitation of iron

Since these cited works on classification of meromictic lakes, many meromictic lakes have been scientifically investigated and reported. Microbiologically controlled chemical reactions, e.g., iron meromixis (Hongve 2002), have been understood more in detail, and their contribution to the density of monimolimnetic waters can be evaluated (e.g., Dietz et al. 2012; Nixdorf and Boehrer 2015). Boehrer and Schultze (2008) refer to the importance of evaluating all processes that are known from scientific literature for sustaining meromixis, since several processes may be acting simultaneously. Here we explain the important processes that can sustain meromixis and support each of these processes by the clearest representations we know of in the environment.

To provide a better overview, we list all the processes that have been documented to form and sustain meromixis, before we go into the details and mention the representative examples form the literature. We mainly see a distinction into two groups: those which operate purely mechanically (where we include salt exclusion at ice formation) and those at which geochemistry of lake waters takes the control. Though we treat the geochemistry as a set of chemical reactions, many of these processes are mediated by organisms. For details, we refer to the subsequent sections and chapters of this book.

1. Purely mechanical:
   (a) Salty inflows into lakes:
       From external sources
       From groundwater
   (b) Freshwater onto salty lakes:
       From external sources
       Salt exclusion at ice formation
   (c) Partial deepwater renewal:
       Evaporation in side bays
       Cooling in side bays
       Salty intrusions from ice
2. Involving geochemistry:
   (a) Decomposition of organic material
   (b) Iron meromixis
   (c) Temperature-dependent solubility of mirabilite
   (d) Calcite precipitation

The local distribution of these mixing and stratifying processes is shown in a schematic display of a lake (Fig. 2.4).

Salty inflows that find their way to the deep layers of a lake can form a permanent stratification, no matter whether these inflows enter at the surface of lakes (Lake Nitinat, Canada: Ozretich 1975) or as groundwater (see Fig. 2.4; Kongressvatn, Norway: Bøyum and Kjensmo 1970; Wallendorfer See and Rassnitzer See, Germany: Böhrer et al. 1998; Heidenreich et al. 1999; Waldsee, Germany: von Rohden et al. 2009, 2010; see also Chaps. 6 and 12 for more

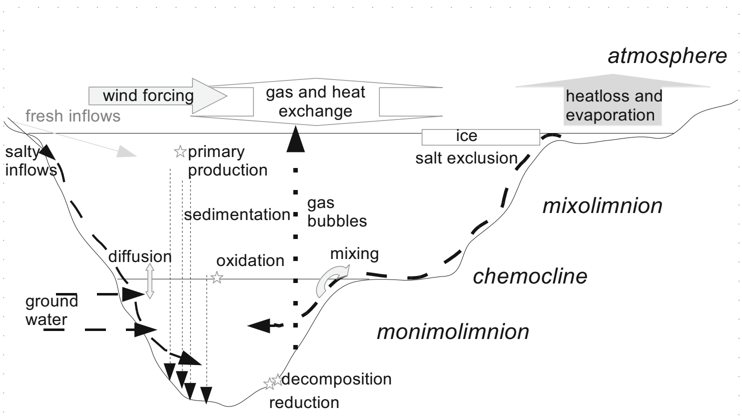

Fig. 2.4 Sketch of processes involved in sustaining meromixis

examples). Sibert et al. (2015) reported meromixis caused by salty wastes entering the lakes and formed by salt used for de-icing of roads; Scharf and Oehms (1992) also reported the same for meromixis in Lake Schalkenmehrener Maar (Germany). High-salinity water can also be produced in the lake itself by enhanced evaporation in a shallow side bay, as in the Dead Sea in the period before 1979 (Nissenbaum 1969). Because only a small portion of the monimolimnion is replaced, the monimolimnion chemistry (e.g., oxygen concentration) is not greatly affected. Salt exclusion during ice formation can also act as a source of saline water (Antarctic lakes: Kerry et al. 1977; Gibson 1999).

In addition, density stratification in the mixolimnion is reinforced when less saline ice melts in spring and forms a water layer of reduced density near the surface, which needs to be removed before turbulent kinetic energy can effectively erode the density stratification at the upper edge of the monimolimnion (e.g., Lake Shira, Russia, Chap. 5). Snowmelt in the vicinity of meromictic lakes and freshwater runoff from snowmelt add to the effect of melting lake ice (e.g., Hammer 1994; Zachara et al. 2016). During wet season, high runoff may also support meromixis by bridging the density stratification into the thermal stratification period especially in regions where precipitation occurs almost exclusively seasonally (e.g., Santofimia et al. 2012). They also reported a full overturn when the precipitation came too late in the year to accomplish the bridging. High precipitation and consequently higher freshwater inflows have stopped some lakes from circulating for several years (e.g., Lake Mono, USA, see Chap. 11: Jellison and Melack 1993; Jellison et al. 1998; Caspian Sea: Peeters et al. 2000; Lake Van, Turkey: Kaden et al. 2010). Similarly, meromictic lakes were formed where fjords have been disconnected from the ocean by land rising after glaciers had receded at the end of the ice age, e.g., Rørholtfjorden, Norway (Strøm 1957); Powell Lake, Canada (Williams et al. 1961); and lakes in coastal regions in the northern Baltic Sea (Lindholm 1996). Some of these lakes maintained their stratification for several thousand years. Seawater was capped with freshwater to create a meromictic lake in the former Island Copper Mine (Canada; see Chap. 9). Controlled freshwater input in lakes Wallendorf and Rassnitz (west of Leipzig, Germany) was used to quantify the effect of shielding the deepwater stratification by a freshwater introduction (Boehrer et al. 2014).

In principle, density-driven flows as described above can also be caused by temperature differences. However, density difference due to temperature is limited to 2 kg/m or 3 kg/m, while density differences due to solute concentration can be one to two orders of magnitude higher. In addition, molecular diffusion of heat is faster (factor ~100) than diffusion of solutes, and hence a density stratification due to temperature is more affected by diffusion. Thus, meromictic lakes due to temperature-driven flows are rare. Similarly, Dead Sea (before 1979), where evaporation created saltier and hence denser water in the south basin, is a good example of creation of meromixis: also surface cooling during southern winter at the south end of Lake Malawi/Nyasa (Malawi, Tanzania, Mozambique) produces sufficiently dense water to intrude the monimolimnion (Vollmer et al. 2002a). Lakes with partial deepwater renewal are called meromictic, only if a sufficient portion of the monimolimnion is replaced to sustain the stratification, but not enough to make dissolved oxygen to be detectable in the monimolimnion.

In addition to water currents, solute precipitation can effectively transport matter through the water column. If salts of high sodium and sulfate concentration are excluded from the ice formation, mirabilite ($Na_2SO_4 \cdot 10H_2O$) may precipitate. Hammer (1994) reports such precipitation below the ice at temperature close to 0 °C for Waldsea Lake (Canada). The settling mirabilite removes solutes—and hence their density contribution—from the cold surface water, but it gets redissolved in the monimolimnion due to the higher temperatures (5–7 °C; Hammer and Haynes 1978) and the strong dependence of mirabilite solubility on temperature (Marion and Farren 1999; see also Chap. 3). The density contribution is added to the monimolimnetic waters. The picture gets slightly more complex when biogenic calcite formation accompanies photosynthesis. With increasing photosynthetic activity, pH increases such that carbonate will form from dissolved bicarbonate in the epilimnion. Eventually the solubility product of calcite is exceeded, and calcite precipitates and sinks to deeper layers. High CO_2 partial pressure in the monimolimnion, e.g., from decomposed organic material, allows a redissolution of calcite (Lake La Cruz, Spain: Rodrigo et al. 2001; see also Chap. 8). Also in this case, the calcite removes the density contribution of solutes from the mixolimnetic waters and adds it to monimolimnetic waters.

Waldsea Lake (Canada) and Lake La Cruz (Spain) demonstrate that reactivity of solutes can inhibit the deep recirculation, but only, if this process transports solutes up the gradients, which means from low concentrations in the mixolimnion to high concentrations in the monimolimnion, effectively enough to compensate for the diffusive and turbulent transport down-gradient. This is facilitated by limited solubility of a substance: particulate solids are formed and precipitate and sink down to the monimolimnion. If conditions in the monimolimnion are favorable, these precipitates can redissolve at least in part. To keep this chemical cycling of matter going, an energy source must be accessible. In nearly all cases, energy is provided by organic material, which has gained its energy from photosynthesis, and feeds it into the chemical cycle on being decomposed. Organisms usually have a slightly higher density than water, and hence they settle to the lake bottom still alive or after they die. Organic material can be oxidized by microorganism, releasing CO_2, which contributes effectively to water density. The oxidizing agent in this process is important, as the net effect of released products must yield a considerable increase in density. Both oxygen (classic biogenic meromixis) and iron (iron meromixis) are good oxidizing agents to raise density sufficiently in the monimolimnion. Also other oxidizing agents (nitrate or sulfate) may be present, but they have not yet been demonstrated to be the primary factor for building the density gradient needed for meromixis.

Iron is present in many mine lakes but also in natural lakes originating from the soil and rocks in the catchments. However, if dissolved oxygen is present in the mixolimnion and if in the upper part of the chemocline, iron gets oxidized to ferric iron Fe(III), it precipitates as hydroxide in water at pH above 3.5 (e.g., Stumm and Morgan 1996). On the contrary, in a monimolimnion where no dissolved oxygen is

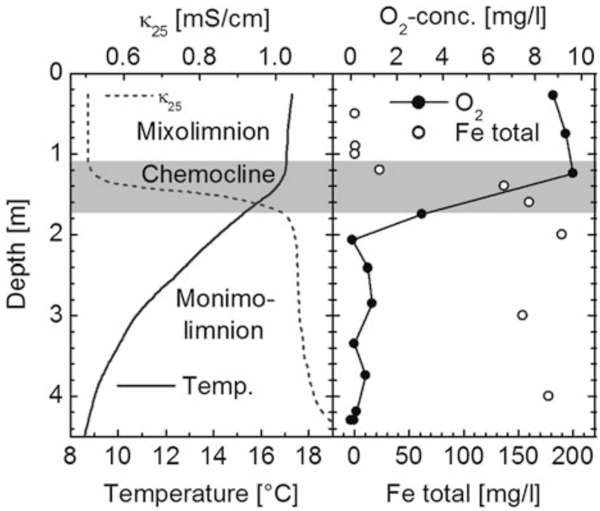

Fig. 2.5 Profiles of temperature and electrical conductance (*left panel*) and total iron and dissolved oxygen (*right panel*) from Lake Waldsee near Döbern, Germany (taken from Boehrer et al. 2009)

available but enough organic material (Fig. 2.5), ferric iron can be used as oxidizing agent and remain dissolved in the reduced form as ferrous iron Fe(II) (e.g., Campbell and Torgerson 1980). Consequently, both iron and the produced CO_2, as well as corresponding bicarbonate, contribute to density of monimolimnetic waters, while in the mixolimnion, iron concentrations and CO_2 concentrations are very low because of low solubility and the escape to the atmosphere (Kjensmo 1967, 1988; Campbell and Torgerson 1980; Hongve 1997, 2002). In Lake Waldsee (Germany), both iron and the carbonate system contribute about the same amount to the density difference between mixolimnion and monimolimnion (Dietz et al. 2012). Manganese can play a similar role as iron, but meromixis dominated by manganese is rare (Nordbytjernet, Norway; Hongve 1997, 2002). A detailed presentation of the biogeochemical processes mentioned above is given in Chap. 3. Also suspended material adds density to lake water. Casamitjana and Roget (1993) claim that the Lake Banyoles, Spain, is kept meromictic by continuously suspended particles. Similarly, Frey (1955) claimed that a turbidity inflow into Längsee (Austria) initiated meromixis in the lake.

Finally, there are lakes that do not fully turn over during the annual cycle: at any time, a profile will show stable density stratification. In these lakes, permanent stratification can be accomplished by thermobaric effects (Lake Shikotsu, Japan: Yoshimura 1935, 1936; Boehrer et al. 2008; Crater Lake, USA: Crawford and Collier 2007; Lake Baikal, Russia: Carmack and Weiss 1991) or by partial deep-water renewal (Issyk Kul, Kyrgyzstan: Vollmer et al. 2002b; Peeters et al. 2003; Lake Baikal, Russia: Weiss et al. 1991; Kondenev 2001). However, such lakes are usually not called meromictic as their deep waters are not permanently anoxic. In addition, the exchange in the monimolimnion is so fast that no considerable accumulation of chemicals is possible in the deep water, and, thus, no pronounced chemical differences are found through the water column.

2.3 Accumulation of Substances

If lakes are density stratified as is mostly the case, vertical transport of substances requires energy to compensate for the potential energy of the system. However, advection of turbulent kinetic energy is inhibited, as long as stratification persists. Internal waves can propagate kinetic energy through density stratification. This kinetic energy creates shear stress at the side boundaries which finally results in mixing. However, the amount of supplied energy is limited.

The complete overturn, which effectively transports solutes from the deepest point quasi-instantaneously to the lake surface, is missing in meromictic lakes. As demonstrated for iron meromixis above, we find an accumulation of substances in the monimolimnion. These substances include iron, which can precipitate as iron hydroxides, and also substances that are flocculated during this process, like organic substances and nutrients. In the deep zones of lakes, the binding of the coprecipitates may be terminated, and hence high concentrations of DOC and nutrients (e.g., phosphorus) can be the result. Primary production and connected uptake of nutrients below the chemocline are limited by low irradiance. Solutes can be stored in monimolimnia at high concentration. In general, concentration of dissolved ionic substances is limited by the solubility product of cations and anions. If this limit is exceeded, precipitation removes the excess portion. In summary, downward transport, incomplete mixing, and limited biogeochemical uptake promote the accumulation of dissolved substances in monimolimnia.

As the continuous supply of oxygen to the monimolimnion is suppressed, we can find substances in chemically reduced form (ferrous iron, ammonium, sulfide, dissolved organic matter (DOM)/DOC, etc.) at concentrations that are not encountered in holomictic lakes or only exceptionally in the mixolimnion. Methane is stable in the chemical setting of many monimolimnia. Reduced sulfur may be found as hydrogen sulfide, if no suitable cation is present to precipitate it from the water column. Hydrogen sulfide is poisonous to many organisms; if released from the water, its unpleasant odor is a nuisance also at distance from the shoreline and can restrict leisure activities on a lake and in its immediate surroundings (e.g., Lower Mystic Lake, USA: Ludlam and Duval 2001). Table 3.1 provides examples for high monimolimnetic concentrations of reduced chemical species (Sect. 3.1). Chapters 5–12 add further examples.

In addition, dissolved gases may accumulate in the monimolimnion (e.g., Aeschbach-Hertig et al. 1999). Monimolimnia are sheltered from direct exchange with the atmosphere. Hence, gases need to be transported upward by diffusive transport through the chemocline and the mixolimnion before they are exchanged with the atmosphere. In addition, the hydrostatic pressure in the deep layers of lakes facilitates the accumulation of gases, beyond atmospheric pressure. According to its concentration c_i, any dissolved volatile substance i produces a gas pressure (Henry law):

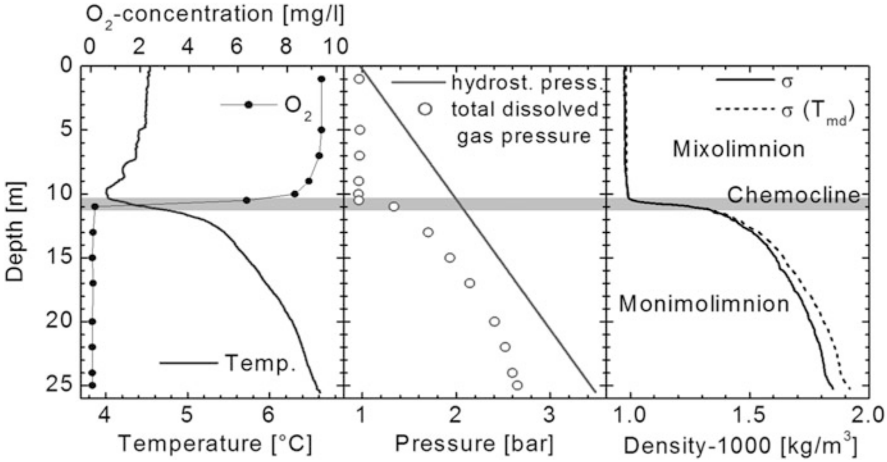

Fig. 2.6 Measured profiles of temperature, oxygen concentration (*left panel*) and gas pressure (symbols in *central panel*) in Lake Vollert-Süd (south of Leipzig, Germany). For comparison, absolute hydrostatic pressure (*central panel*) and density based on temperature and electrical conductivity measurements are included (*solid line*, *right panel*) and density at given electrical conductivity at a temperature of constant 4 °C (*dashed line*, *right panel*)

$$p_i = c_i / H_i \tag{2.1}$$

where H_i is a specific temperature-dependent constant (Henry coefficient) (e.g., Sander 1999).

If a strong gas source is available, gas accumulation may continue up to a critical point where the sum of gas pressures equals absolute pressure (see Fig. 2.6; atmospheric pressure p_a plus hydrostatic pressure p_h):

$$\sum_i p_i = p_a + p_h \tag{2.2}$$

From this point, ebullition occurs.

Because of its high solubility (large Henry coefficient), CO_2 can reach concentrations of several liters per liter of water, as reported for Lake Nyos (Cameroon; Kling 1988). In this lake, some trigger mechanism released a large amount of the stored CO_2 gas and asphyxiated 1700 human beings in the lake surroundings (Kling et al. 1987). At least three more lakes are known where gas accumulation is a matter of concern: Lake Monoun, Cameroon (Rouwet et al. 2015); Kabuno Bay of Lake Kivu, Rwanda/Congo (Schmid et al. 2004a); and Guadiana pit lake in Herrerias Mine, Spain (Sánchez-España et al. 2014). Controlled degassing can remove the risks related to gas accumulations (e.g., Halbwachs et al. 2004; Boehrer et al. 2016). Also methane (e.g., Black Sea, McGinnis et al. 2006; Lake Matano, Indonesia, Chap. 10) and hydrogen sulfide are known to accumulate in monimolimnia. In Lake Kivu, methane concentrations are high enough for commercial exploitation (Tietze et al. 1980; Wüest et al. 2012).

2.4 Density Approaches

In meromictic lakes, dissolved substances play an important role for sustaining the stratification. Each solute contributes its share in density. If the composition of solutes is known, density can be calculated accurately from coefficients of partial molal volumes listed in the scientific literature of physical chemistry. Boehrer et al. (2010) included the partial molal volumes of limnologically important solutes in a convenient algorithm RHOMV, i.e., density ρ from partial molal volumes.

In addition, electrical conductivity is used as a quantitative bulk measure for the amount of dissolved substances. Electrical conductivity is easy to measure, e.g., by automatic probes, at high resolution and high accuracy. In conclusion, electrical conductivity has been used to calculate the density contribution of solutes to natural waters. In general, oceanographic formulae (UNESCO, Fofonoff and Millard 1983, International Organization for Standardization (ISO) 1985, TEOS-10) do not reflect the effect of solutes accurately for limnic waters (also Chen and Millero 1986), especially as meromictic lakes often show either high concentrations or unusual composition of solutes at least from an oceanographic point of view (e.g., tabled saline lakes in books by Hammer 1986 and Kalff 2002). To improve density calculations, Moreira et al. (2016) provided a numerical approach to evaluate a correlation between electrical conductivity and density for any chemical lake water composition. A simple formula is proposed for adding the density contribution of solutes to the density of pure water ρ_W from temperature T and electrical conductivity κ_{25} out of CTD profiles. Only two lake-specific coefficients λ_0 and λ_1 need to be determined:

$$\rho = \rho_W(T) + \kappa_{25}(\lambda_0 + \lambda_1 \cdot (T - 25\,^\circ\mathrm{C})) \tag{2.3}$$

Both RHOMV and Moreira's density calculator can be used or downloaded from the Internet (Fig. 2.7). Calculations show that solute contributions to density are underestimated by typically between 20 % and 100 % with oceanographic approaches. Better accuracy can be achieved by measuring density of lake water and correlating the results with electrical conductivity and temperature (e.g., Jellison et al. 1999; Karakas et al. 2003). Sufficiently precise methods for in situ measurements of density in lakes are not available (Gräfe et al. 2002).

Dietz et al. (2012) showed that density differences can easily be calculated from "specific density fraction" as long as concentrations are in the freshwater range (<3 g/L). The authors have shown that in iron-meromictic Waldsee (Germany), the density difference between mixolimnion and monimolimnion is caused by higher concentration of iron and carbon species (CO_2, bicarbonate, DOC) in roughly equal parts.

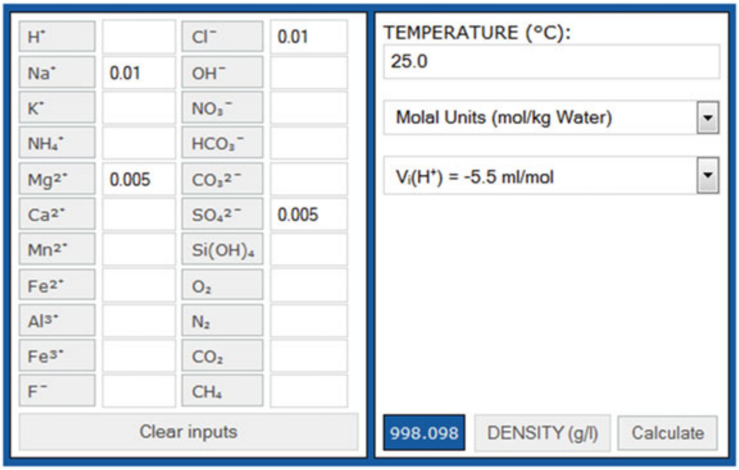

Fig. 2.7 The input mask for RHOMV on www.ufz.de/webax for easy calculation of density for given salt composition

2.5 Transport Under Conditions of Permanent Stratification

The stratification in meromictic lakes is often looked upon as very static phenomenon. Expressions like "permanently stratified" give the impression of an eternally sealed-off monimolimnion. This is not correct: we have already mentioned about discernible exchange processes between mixolimnion and monimolimnion and through the chemocline. The sharp interface would be smoothened by diffusion, but other transport processes cut the diffuse ends off and carry material away from (or to) the chemocline.

Meromixis sustained by salty inflows (surface or groundwater) is a result of flushing the monimolimnion. For example, renewal time for the Waldsee (Germany) monimolimnion is around one year (von Rohden et al. 2009). The volume of the monimolimnion would increase, if there were no volume losses due to monimolimnion erosion through turbulence and subsequent inclusion of the water into the mixolimnion. This is also true for lakes with partial renewal of the monimolimnion from sources within the lake (e.g., saltwater formation in south basin of Dead Sea before 1979: Nissenbaum 1969, Lerman et al. 1995; cold waters at south end of Lake Malawi/Nyasa: Vollmer et al. 2002a).

These erosive effects have been documented in Lake Mono (Jellison and Melack 1993, Jellison et al. 1998) and quantitatively measured in Waldsee (Germany; von Rohden et al. 2009) and Wallendorfer See and Rassnitzer See (Germany; Boehrer et al. 2014). In most cases, erosion of the monimolimnion takes place during intense recirculation periods, i.e., in winter. In Waldsee (Germany), this effect happens during nocturnal cooling during summer. Depending on weather conditions, the shaving off of the monimolimnion can be more or less intensive, leading to irregular inputs of solutes, e.g., nutrients, into the mixolimnion.

Precipitation of solutes from the mixolimnion—as discussed above in the processes forming meromixis—is a very effective process. Other than the transport of solutes, precipitates transport almost exclusively the substances of interest and only little water. As most precipitates have negative buoyancy in water, they settle to the lake bed. A redissolution in the monimolimnion can result in a transport against the concentration gradient, i.e., from the low-concentrated mixolimnion to the highly concentrated monimolimnion. In the opposite direction, ebullition can remove volatile substances from the monimolimnion. In most cases, the gases are released into the atmosphere at the lake surface. However, also redissolution on the path into mixolimnetic waters is possible (e.g., Black Sea: McGinnis et al. 2006).

Even under weak water movements, dissolved molecules move driven by thermal motion. The result is the diffusion in water at a rate of $D \sim 10^{-9}$ m^2/s. An initially sharp interface becomes smoother over a time period t at a rate of the order of magnitude of

$$\delta \sim (Dt)^{0.5} \tag{2.4}$$

Thus, an originally perfectly sharp interface will smoothen to an interface of close to 1 m in about a year. This is very slow and diffusive transports are less effective than turbulent transport processes.

Several mechanisms create instabilities in the open waters (e.g., Imboden and Wüest 1995), but for small- and middle-sized lakes, mixing in the deep water is dominated by processes acting close to the side walls (e.g., Goudsmit et al. 1997). Flows over rough terrain create current shear and hence turbulence, and together with the retention of water in the interspaces of coarser sediment, contribute the bulk of the transport of dissolved substances. High-density gradients result in small vertical excursions of water movements and hence small vertical transport. Under the assumption that at any depth z, the same amount of energy E is transferred into mixing at an efficiency of γ, we expect a relation for the vertical transport coefficients K_z of the form

$$K_z(z) = \gamma \cdot E/N^2 \quad \text{where} \quad N^2(z) = -\frac{g}{\rho}\frac{\partial \rho}{\partial z} \tag{2.5}$$

Brunt-Väisälä frequency (squared) represents the density ρ gradient along the vertical axis z against earth acceleration g. Transport coefficients measured by spiking the deep water with the artificial tracer SF_6 revealed the strong dependence of transport on density stratification (von Rohden and Ilmberger 2001). At levels of highest stratification in lakes Wallendorf and Rassnitz (Germany), vertical transport was close to molecular levels for both heat and solutes. In a number of fjord lakes, seawater was trapped in the deep layers for thousands of years (e.g., in Salsvatn (Norway) for ca. 3000 years, Bøyum 1973; in Rørholtfjorden (Norway) ca. 6000 years, Strøm 1963; and in Powell Lake (Canada) 9000–11,000 years, Williams et al. 1961). Vertical mixing was so low that even today part of this seawater can be found in the deepest areas of the lakes. In conclusion, the effective turbulent mixing was only little higher than molecular diffusion. In fact in Powell Lake (Canada), it is claimed that the different distribution of ions stems from the differences in molecular diffusivity of these substances (Sanderson et al. 1986).

In comparison with solutes, diffusive transport of heat is two orders of magnitude faster. Consequently, deep waters stratified by dissolved substances can show double diffusion, if temperature gradients inflict a reduction of the density gradient (see also Brandt and Fernando 1996; Boehrer 2012). In initially stable zones with disappearing turbulence, the greatly higher diffusivity of heat than that of solutes can impose locally unstable conditions, which form thin convection cells (decimeters) of large horizontal extension (kilometers) (Newman 1976; Schmid et al. 2004b; von Rohden et al. 2010), separated by even thinner layers of strong density gradients (Fig. 2.8). Vertical transport of solutes as a consequence is controlled by the local production of convection and turbulence as a result of double-diffusive convection and can, therefore, be considerably more efficient than molecular diffusivity (e.g., Schmid et al. 2004b). In Waldsee, the monimolimnetic overturn was clearly driven by double-diffusive effects modified by chemical reactivity of solutes (Boehrer et al. 2009).

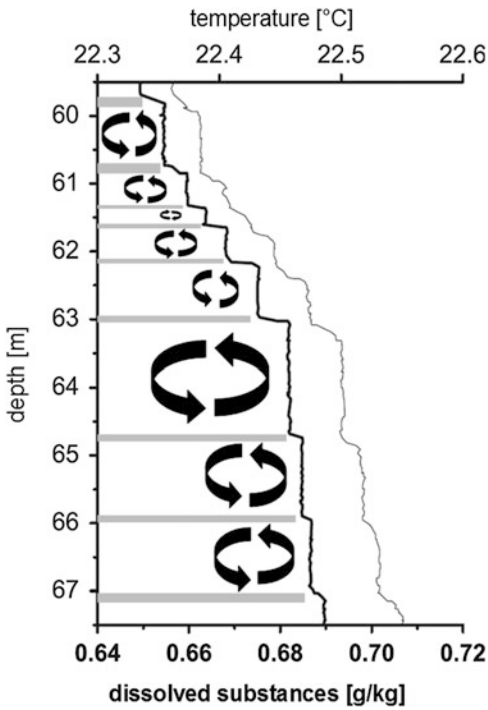

Fig. 2.8 Double-diffusive convection cells creating a staircase of the concentration of dissolved substances (*fine line*) and temperature (*thick line*) in a profile of Lake Nyos, Cameroon (modified from Schmid et al. 2004b). Convection cells, several decimeters thick, alternate with layers of no convection (in *gray*), where heat is transported diffusively (from Boehrer 2012)

Because transport through density gradients at chemoclines is slow, it has created interest in utilizing deep waters for the disposal or the confinement of undesirable substances (organics from lignite processing: Stottmeister et al. 1998; heavy metals: Fisher 2002; Fisher and Lawrence 2006; see also Sects. 9.4 and 9.5) in monimolimnia. Notably, the sealing is not perfect and transport still happens (Stevens and Lawrence 1997). Also heat can be trapped in monimolimnia of so-called solar ponds, to store energy or to culture organisms requiring higher water temperatures in colder climates (Weinberger 1964; Kirkland et al. 1983; Bozkurt et al. 2015). Since aspects of management are particularly relevant for meromictic pit lakes, such issues are discussed in Sect. 9.5, and an example is provided in Sect. 9.4 of Chap. 9.

2.6 Concluding Remarks

Meromictic waterbodies are subdivided into two chemically different water layers. While the upper layer (epilimnion or mixolimnion) is subject to exchange with the atmosphere, the deep water (monimolimnion) is isolated and hence does not receive any oxygen from the atmosphere. As this situation is generally maintained for long periods, other dissolved substances accumulate in the monimolimnion in a chemically reduced form.

The chemocline usually represents a sharp transition within a few decimeters (sometimes meters) between the mixolimnion and the monimolimnion. The higher concentration of solutes is usually responsible for the greater stability of the density-induced stratification. Consequently, the chemocline also represents a density gradient, i.e., pycnocline. Settling particles of a density between mixolimnion water and monimolimnion water can find their level of neutral buoyancy within the chemocline. Such particles may be found floating within the chemocline.

In the chemocline, substances from mixolimnion and monimolimnion get into contact and can react with each other, even supplying energy, e.g., dissolved iron from monimolimnion and dissolved oxygen from the mixolimnion. Such zones can be identified by their turbidity through visual inspection (Fig. 2.3). Although most of the reactions are mediated by organisms, the exothermal nature of reactions facilitates the reaction, without involvement of an additional energy source, e.g., light for photosynthesis.

References

Aeschbach-Hertig W, Hofer M, Kipfer R, Imboden DM, Wieler R (1999) Accumulation of mantle gases in a permanently stratified volcanic lake (Lac Pavin, France). Geochim Cosmochim Acta 63:3357–3372

Boehrer B (2012) Double-diffusive convection in lakes. In: Bentsson L, Herschy RW, Fairbridge RW (eds) Encyclopedia of lakes and reservoirs. Springer, Dordrecht, pp 223–224

Boehrer B (2013) Physical properties of acidic pit lakes. In: Geller W, Schultze M, Kleinmann R, Wolkersdorfer C (eds) Acidic pit lakes. Springer, Heidelberg, pp 23–42
Boehrer B, Schultze M (2008) Stratification of lakes. Rev Geophys 46:RG2005. doi:10.1029/2006RG000210
Boehrer B, Matzinger A, Schimmele M (2000) Similarities and differences in the annual temperature cycles of East German mining lakes. Limnologica 30:271–279
Boehrer B, Fukuyama R, Chikita K (2008) Stratification of very deep, thermally stratified lakes. Geophys Res Lett 35:L16405. doi:10.1029/2008GL034519
Boehrer B, Dietz S, von Rohden C, Kiwel U, Jöhnk KD, Naujoks S, Ilmberger J, Lessmann D (2009) Double-diffusive deep water circulation in an iron-meromictic lake. Geochem Geophys Geosyst 10:Q06006. doi:10.1029/2009GC002389
Boehrer B, Herzsprung P, Schultze M, Millero FJ (2010) Calculating density of water in geochemical lake stratification models. Limnol Oceanogr Methods 8:567–574. doi:10.4319/lom.2010.8.567
Boehrer B, Kiwel U, Rahn K, Schultze M (2014) Chemocline erosion and its conservation by freshwater introduction to meromictic salt lakes. Limnologica 44:81–89
Boehrer B, Yusta I, Magin K, Sanchez-España J (2016) Quantifying, assessing and removing the extreme gas load from meromictic Guadiana pit lake, Southwest Spain. Sci Total Environ 563–564:468–477
Böhrer B, Heidenreich H, Schimmele M, Schultze M (1998) Numerical prognosis for salinity profiles of future lakes in the open cast mine Merseburg-Ost. Int J Salt Lake Res 7:235–260
Bøyum A (1973) Salsvatn, a lake with old sea water. Schweiz Zeitschr Hydrol 35:262–277
Bøyum A, Kjensmo J (1970) Kongressvatn. A crenogenic meromictic lake at Western Spitsbergen. Arch Hydrobiol 67:542–552
Bozkurt I, Mantar S, Karakilcik M (2015) A new performance model to determine energy storage efficiencies of a solar pond. Heat Mass Transf 51:39–48
Brandt A, Fernando HJS (eds) (1996) Double diffusive convection. Geophys Monogr Ser, vol 94. AGU, Washington, DC, p 334
Campbell P, Torgersen T (1980) Maintenance of iron meromixis by iron redeposition in a rapidly flushed monimolimnion. Can J Fish Aquat Sci 37:1303–1313
Carmack EC, Weiss RF (1991) Convection in Lake Baikal: an example of thermobaric instability. In: Chu PC, Gascard, JC (eds) Deep convection and deep water formation in the Oceans. Elsevier, Amsterdam, pp 215–228,
Casamitjana X, Roget E (1993) Resuspension of sediment by focused groundwater in Lake Banyoles. Limnol Oceanogr 38:643–656
Chen C-TA, Millero FJ (1986) Precise thermodynamic properties for natural waters covering only the limnological range. Limnol Oceanogr 31:657–662
Crawford GB, Collier RW (2007) Longterm observations of hypolimnetic mixing in Crater Lake, Oregon. Hydrobiologia 574:47–68
Dietz S, Lessmann D, Boehrer B (2012) Contribution of solutes to density stratification in a meromictic lake (Waldsee/Germany). Mine Water Environ 31:129–137
Eloranta P (1999) Light penetration and thermal stratification in lakes. In: Keskitalo J, Eloranta P (eds) Limnology of humic waters. Backhuys Publishers, Leiden, pp 72–74
Findenegg I (1933) Alpenseen ohne Vollzirkulation. Int Rev Gesamten Hydrobiol Hydrogr 28:295–311
Findenegg I (1935) Limnologische Untersuchungen im Kärntener Seengebiete. Ein Beitrag zu Kenntnis des Stoffhaushaltes in Alpenseen. Int Rev Gesamten Hydrobiol Hydrogr 32:369–423
Findenegg I (1937) Holomiktische und meromiktische Seen. Int Rev Gesamten Hydrobiol Hydrogr 35:586–610
Fisher TSR (2002) Limnology of the meromictic Island Copper Mine pit lake. Dissertation, University of British Columbia
Fisher TSR, Lawrence GA (2006) Treatment of acid rock drainage in a meromictic pit lake. J Environ Eng 132:515–526

Fofonoff NP, Millard RC Jr (1983) Algorithms for commutation of fundamental properties of seawater. UNESCO Tech Pap Mar Sci 44

Frey DG (1955) Längsee: a history of meromixis. Mem Ist Ital Idrobiol Suppl 8:141–164

Gibson JAE (1999) The meromictic lakes and stratified marine basins of the Vestfold Hills, East Antarctica. Antarct Sci 11:175–192

Goudsmit G-H, Peeters F, Gloor M, Wüest A (1997) Boundary versus internal diapycnal mixing in stratified natural waters. J Geophys Res 102(C13):27903–27914

Gräfe H, Boehrer B, Hoppe N, Müller SC, Hauptmann P (2002) Ultrasonic in situ measurements of density, adiabatic compressibility, and stability frequency. Limnol Oceanogr 47:1255–1260

Halbwachs M, Sabroux J-C, Grangeon J, Kayser G, Tochon-Danguy J-C, Felix A, Beard J-C, Villevielle A, Voter G, Richon P, Wuest A, Hell J (2004) Degassing the "Killer Lakes" Nyos and Monoun, Cameroon. Eos Trans AGU 85:281–285

Hammer UT (1986) Saline lake ecosystems of the world. Dr W Junk Publishers, Dordrecht

Hammer UT (1994) Life and times of five Saskatchewan saline meromictic lakes. Int Rev Gesamten Hydrobiol 79:235–248

Hammer UT, Haynes RC (1978) The saline lakes of Saskatche-wan. II. Locale, hydrography and other physical aspects. Int Rev Gesamten Hydrobiol 63:179–203

Heidenreich H, Boehrer B, Kater R, Hennig G (1999) Gekoppelte Modellierung geohydraulischer und limnophysikalischer Vorgänge in Tagebaurestseen und ihrer Umgebung. Grundwasser 4: 49–54

Hongve D (1997) Cycling of iron, manganese, and phosphate in a meromictic lake. Limnol Oceanogr 42:635–647

Hongve D (2002) Seasonal mixing and genesis of endogenic meromixis in small lakes in Southeast Norway. Nord Hydrol 33:189–206

Hutchinson GE (1937) A contribution to the limnology of arid regions: primarily founded on observations made in the Lahontan basin. Trans Connecticut Acad Arts Sci 33:47–132

Hutchinson GE (1957) A treatise on limnology, Geography, physics and chemistry, vol 1. Wiley, New York

Imboden DM, Wüest A (1995) Mixing mechanisms in lakes. In: Lerman A, Imboden DM, Gat JR (eds) Physics and chemistry of lakes. Springer, Berlin, pp 83–138

International Organization for Standardization (ISO) (1985) Water quality: determination of electrical conductivity, Standard 7888. ISO, Geneva

Jellison R, Melack JM (1993) Meromixis in hypersaline Mono Lake, California. 1. Vertical mixing and density stratification during the onset, persistence, and breakdown of meromixis. Limnol Oceanogr 38:1008–1019

Jellison R, Romero J, Melack JM (1998) The onset of meromixis during restoration of Mono Lake, California: unintended consequences of reducing water diversions. Limnol Oceanogr 43: 706–711

Jellison R, MacIntyre S, Millero FJ (1999) Density and conductivity properties of NA-CO_3-Cl-SO_4 brine from Mono Lake, California, USA. Int J Salt Lake Res 8:41–53

Kaden H, Peeters F, Lorke A, Kipfer R, Tomonaga Y, Karabiyikoglu M (2010) Impact of lake level change on deep-water renewal and oxic conditions in deep saline Lake Van, Turkey. Water Resour Res 46:W11508. doi:10.1029/2009WR008555

Kalff J (2002) Limnology, 2nd edn. Prentice Hall, Upper Saddle River, NJ

Karakas G, Brookland I, Boehrer B (2003) Physical characteristics of acidic Mining Lake 111. Aquat Sci 65:297–307

Kerry KR, Grace DR, Williams R, Burton HR (1977) Studies on some saline lakes of the Vestfold Hills, Antarctica. In: Llano GAS (ed) Adaptations within antarctic ecosystems. Gulf, Houston, Texas, pp 839–858

Kirkland DW, Platt Bradbury J, Dean WE (1983) The heliothermic lake—a direct method of collecting and storing solar energy. Arch Hydrobiol Suppl 65:1–60

Kjensmo J (1967) The development and some main features of "ironmeromictic" soft water lakes. Arch Hydrobiol 32:137–312

Kjensmo J (1988) Post-glacial sediments and the stagnation history of the iron-meromictic Lake Skjennungen, Eastern Norway. Arch Hydrobiol 113:481–499
Kling GW (1988) Comparative transparency, depth of mixing and stability of stratification in lakes of Cameroon, West Africa. Limnol Oceanogr 33:27–40
Kling GW, Clark MA, Compton HR, Devine JD, Evans WC, Humphrey AM, Koenigsberg EJ, Lockwood JP, Tuttle ML, Wagner GN (1987) The 1986 Lake Nyos gas disaster in Cameroon, West Africa. Science 236:169–175
Kodenev GG (2001) Deep-water renewal in Lake Baikal. Geol Geofiz 42:1127–1136
Lerman A, Imboden DM, Gat JR (eds) (1995) Physics and chemistry of lakes. 2nd edn, Springer, Berlin
Lindholm T (1996) Periodic anoxia in an emerging coastal lake basin in SW Finland. Hydrobiologia 325:223–230
Ludlam SD, Duval B (2001) Natural and management induced reduction in monimolimnetic volume and stability in a coastal, meromictic lake. Lake Reserv Manag 17:71–81
Marion GM, Farren RE (1999) Mineral solubilities in the Na-K-Mg-Ca-Cl-SO_4-H_2O system: a re-evaluation of the sulfate chemistry in the Spencer-Møller-Weare model. Geochim Cosmochim Acta 63:1305–1318
McGinnis DF, Greinert J, Artemov Y, Beaubien SE, Wüest A (2006) Fate of rising methane bubbles in stratified waters: how much methane reaches the atmosphere? J Geophys Res 111: C09007. doi:10.1029/2005JC003183
Merilainen J (1970) On the limnology of the meromictic Lake Valkiajarvi, in the Finnish lake district. Ann Bot Fenn 7:29–51
Moreira S, Schultze M, Rahn K, Boehrer B (2016) A practical approach to lake water density from electrical conductivity and temperature. Hydrol Earth Syst Sci Discuss 20:2975–2986. doi:10.5194/hess-2016-36
Newman FC (1976) Temperature steps in Lake Kivu: a bottom heated saline lake. J Phys Oceanogr 6:157–163
Nissenbaum A (1969) Studies in the geochemistry of the Jordan River-Dead Sea system. Dissertation, University of California
Nixdorf E, Boehrer B (2015) Quantitative analysis of biogeochemically controlled density stratification in an iron-meromictic lake. Hydrol Earth Syst Sci 19:4505–4515
Ozretich RJ (1975) Mechanisms for deep water renewal in Lake Nitinat, a permanently anoxic fjord. Estuar Coast Mar Sci 3:189–200
Peeters F, Kipfer R, Achermann D, Hofer M, Aeschbach-Hertig W, Beyerle U, Imboden DM, Rozanski K, Fröhlich K (2000) Analysis of deep-water exchange in the Caspian Sea based on environmental tracers. Deep-Sea Res I Oceanogr Res Pap 47:621–654
Peeters F, Finger D, Hofer M, Brennwald M, Livingstone DM, Kipfer R (2003) Deep-water renewal in Lake Issyk-Kul driven by differential cooling. Limnol Oceanogr 48:1419–1431
Rodrigo MA, Miracle MR, Vicente E (2001) The meromictic Lake La Cruz (Central Spain), patterns of stratification. Aquat Sci 63:406–416
Rouwet D, Christenson B, Tassi F, Vandemeulenbrouck J (eds) (2015) Volcanic Lakes. Springer, Heidelberg
Salonen K, Arvola L, Rask M (1984) Autumnal and vernal circulation of small forest lakes in Southern Finland. Verh Int Ver Limnol 22:103–107
Sánchez-España J, Boehrer B, Yusta I (2014) Extreme carbon dioxide concentrations in acidic pit lakes provoked by water/rock interaction. Environ Sci Technol 48:4273–4281
Sander R (1999) Compilation of Henry's law constants for inorganic and organic species of potential importance in environmental chemistry. http://www.mpch-mainz.mpg.de/~sander/res/henry.html. Accessed 15 Jan 2016
Sanderson B, Perry K, Pedersen T (1986) Vertical diffusion in meromictic Powell Lake, British Columbia. J Geophys Res 91(C6):7647–7655
Santofimia E, López-Pamo E, Reyes J (2012) Changes in stratification and iron redox cycle of an acidic pit lake in relation with climatic factors and physical processes. J Geochem Explor 116–117:40–50

Scharf BW, Oehms M (1992) Physical and chemical characteristics. Arch Hydrobiol Beih 38: 63–83
Schmid M, Lorke A, Dinkel C, Tanyileke G, Wüest A (2004a) Double-diffusive convection in Lake Nyos, Cameroon. Deep-Sea Res I 51:1097–1111
Schmid M, Tietze K, Halbwachs M, Lorke A, McGinnis D, Wüest A (2004b) How hazardous is the gas accumulation in Lake Kivu? arguments for a risk assessment in light of the Nyiragongo Volcano eruption of 2002. Acta Vulcanol 14(15):115–122
Sibert RJ, Koretsky CM, Wyman DA (2015) Cultural meromixis: effects of road salt on the chemical stratification of an urban kettle lake. Chem Geol 395:126–137
Stevens CL, Lawrence GA (1997) The effect of subaqueous disposal of tailings in standing waters. J Hydraul Res 35:147–159
Stottmeister U, Weißbrodt E, Becker PM, Pörschmann J, Kopinke FD, Martius GM, Wießner A, Kennedy C (1998) Analysis, behaviour and fate of a lignite pyrolysis wastewater deposit. In: Contaminated soil 98. Thomas Telford, London, pp 113–121
Strøm KM (1957) A lake with trapped sea-water? Nature 180:982–983
Strøm KM (1963) Trapped sea water. New Sci 274:384–386
Stumm W, Morgan JJ (1996) Aquatic chemistry, 3rd edn. Wiley, New York
TEOS-10: IOC, SCOR, and IAPSO (2010) The international thermodynamic equation of seawater–2010: calculation and use of thermodynamic properties. Comm Manuals Guide. http://www.TEOS-10.org. Accessed 15 Jan 2016
Tietze K, Geyh M, Müller H, Schröder L (1980) The genesis of methane in Lake Kivu. Geol Rundsch 69:452–472
Vollmer MK, Weiss RF, Bootsma HA (2002a) Ventilation of lake Malawi/Nyasa. In: Odada EO, Olago DO (eds) The East African great lakes: limnology, paleolimnology and biodiversity. Kluwer, Dordrecht, pp 209–233
Vollmer MK, Weiss RF, Williams RT, Falkner KK, Qiu X, Ralph EA, Romanovsky VV (2002b) Physical and chemical properties of the waters of saline lakes and their importance for deep-water renewal: lake Issyk-Kul, Kyrgyzstan. Geochim Cosmochim Acta 66:4235–4246
von Rohden C, Ilmberger J (2001) Tracer experiment with sulfurhexafluoride to quantify the vertical transport in a meromictic pit lake. Aquat Sci 63:417–431
von Rohden C, Ilmberger J, Boehrer B (2009) Assessing groundwater coupling and vertical exchange in a meromictic mining lake with an SF6-tracer experiment. J Hydrol 372:102–108
von Rohden C, Boehrer B, Ilmberger J (2010) Evidence for double diffusion in temperate meromictic lakes. Hydrol Earth Syst Sci 14:667–674
Walker KF, Likens GE (1975) Meromixis and a reconsidered typology of lake circulation patterns. Verh Int Ver Limnol 19:442–458
Weinberger H (1964) The physics of the solar pond. Sol Energy 8:45–56
Weiss RF, Carmack EC, Koropalov VM (1991) Deepwater renewal and biological production in Lake Baikal. Nature 349:665–669
Wetzel RG (2001) Limnology: lake and river ecosystems, 3rd edn. Academic, San Diego
Williams PM, Mathews WH, Pckard GL (1961) A lake in British Columbia containing old sea water. Nature 191:830–832
Wüest A, Jarc L, Bürgmann H, Pasche N, Schmid M (2012) Methane formation and future extraction in Lake Kivu. In: Descy J-P, Darchambeau F, Schmid M (eds) Lake Kivu—limnology and biogeochemistry of a tropical great lake. Springer, Dordrecht, pp 165–180
Yoshimura S (1935) A contribution to the knowledge of deep water temperatures of Japanese lakes. Part 1. Summer temperature. Jpn J Astron Geophys 13:61–120
Yoshimura S (1936) Deep water temperatures of lakes of Japan in winter. Sea Air 15:195–208
Zachara JM, Moran JJ, Resch CT, Lindemann SR, Felmy AR, Bowden ME, Cory AB, Fredrickson JK (2016) Geo- and biogeochemical processes in a heliothermal hypersaline lake. Geochim Cosmochim Acta 181:144–163. doi:10.1016/j.gca.2016.02.001

http://www.springer.com/978-3-319-49141-7

Ecology of Meromictic Lakes
Gulati, R.D.; Zadereev, E.; Degermendzhi, A.G. (Eds.)
2017, X, 405 p. 91 illus., 27 illus. in color., Hardcover
ISBN: 978-3-319-49141-7