PART II: CHARACTERISTICS AND CLASSIFICATIONS

CHAPTER 5

Stratification and Circulation of Pit Lakes

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INTRODUCTION

Like natural lakes, most mine lakes show a vertical stratification of their water masses at least for some extended time periods. Vertical circulation of the water masses is controlled by heat exchange with the atmosphere and gradients of dissolved substances. Even small density differences, in the range of a fraction of a percent, can prevent a lake from overturning and refreshing the deep waters with oxygen. This has decisive impact on the evolution of water quality and, as a consequence, on the community of living organisms in the lake.

In this chapter, the annual cycle of stagnation periods and circulation periods is described. The relevance of the circulation is indicated, and special features of lakes that do not experience a full overturn are introduced. Important factors contributing to density stratification, such as temperature and dissolved substances, are discussed. Also included is the derivation of the appropriate physical quantities for evaluating the stability of a water column—that is, electrical conductance and potential temperature—from in situ measurements. Finally, mitigative measures are referred to, which can be implemented if natural circulation of the lake does not provide enough oxygen to the deep water.

CIRCULATION PATTERNS

In most climate zones on Earth, surface temperatures of lakes show a pronounced temperature cycle over the year (Figure 5.1). This is a consequence of thermal contact with the atmosphere and the seasonal variation of meteorological parameters, such as incoming solar radiation. The temperatures in the deep water follow the surface temperatures only for a time when the lake is homothermal during winter (Figure 5.1). Throughout summer, temperatures differ between surface and deeper layers. Warmer water floats on top of colder, denser water such that the lake remains stratified. As overturning water parcels would require energy, Lake Goitsche, Germany, shown in Figure 5.1, is called stably stratified during summer.

On the contrary during winter, no density differences obstruct the vertical transport of water parcels. Hence, the annual cycle is divided into a stagnation period and a circulation period. During the circulation period, dissolved substances, such as oxygen or nutrients, are distributed over the entire water body. Hence, the circulation pattern is a decisive factor for the evolution of water quality and in consequence for living organisms in the lake. The following classification of lakes according to their circulation patterns is in common use:

- *Holomictic lakes* overturn and homogenize at least once a year. According to the number of circulation periods, monomictic, dimictic (Figure 5.2), and polymictic lakes are distinguished.

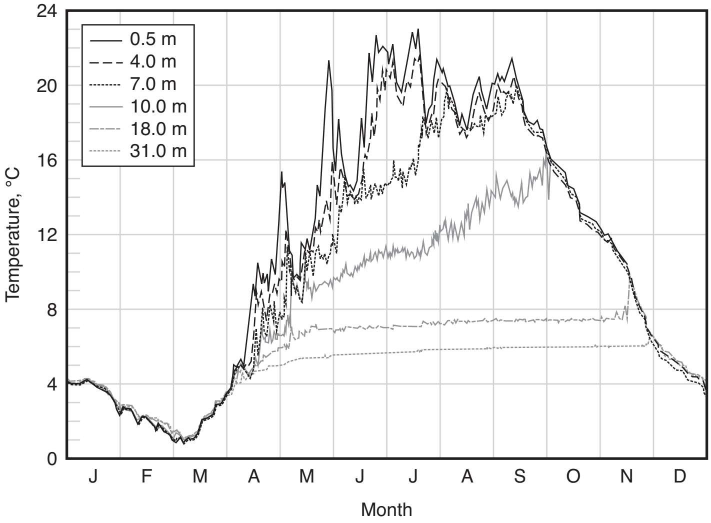


FIGURE 5.1 Temperatures, averaged over 24 hours, at several depths in mine lake Goitsche near Bitterfeld, Germany, during the year 2005

- *Meromictic lakes* are those in which the deep recirculation does not reach the deepest point of the lake. A bottom layer, referred to as the monimolimnion, does not participate in the homogenization and shows pronounced chemical differences, such as anoxia, compared to the mixolimnion (described later).
- *Amictic lakes* do not experience deep recirculation. Usually permanently ice-covered lakes are included in this class. Lakes, however, can also circulate underneath an ice sheet by external forcing.

FORMATION OF LAYERS

Temperature Stratification

While the surface water is exposed to solar radiation and thermal contact with the atmosphere, the deeper layers are sheltered from the major sources of heat. Diffusive heat transport on a molecular level is very slow and takes weeks to transport heat over a vertical distance of 1 m. A much more efficient heat transport is accomplished by turbulent transport. The limited budget of available kinetic energy limits the depth to which a certain amount of heat can be forwarded over the stratification period. In sufficiently deep lakes, the thermal stratification holds until cooler autumn and winter temperatures allow a deeper circulation. The warm surface water layer is called *epilimnion*, whereas the colder water layer beneath, which has not been mixed into the epilimnion over the stratification period, is called *hypolimnion*. A sharp temperature gradient (*thermocline*) forms between both layers (Figure 5.3).

The epilimnion and the atmosphere are in thermal contact and exchange volatile substances with each other. In addition, the epilimnion is circulated episodically by wind events or periods of lower temperatures during the stratification period. In contrast, the hypolimnion is isolated from exchange with the atmosphere during the stratification period. Transport of dissolved matter across the vertical density gradient of the thermocline usually is small.

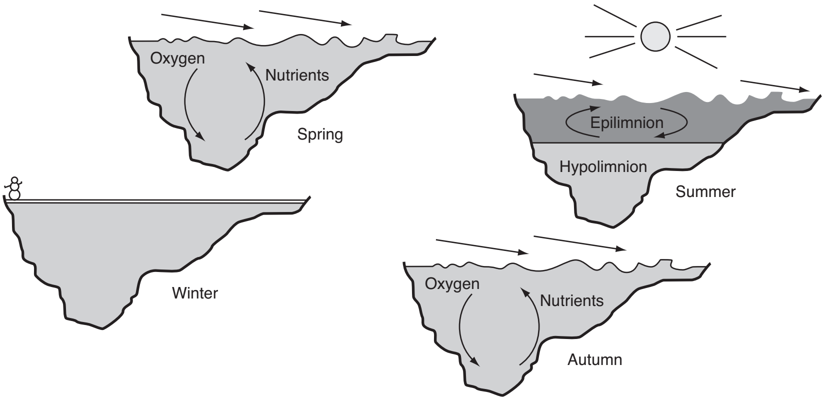


FIGURE 5.2 Annual cycle of a holomictic lake with two circulation periods separated by the presence of an ice cover during winter and thermal stratification during summer (dimictic lake)

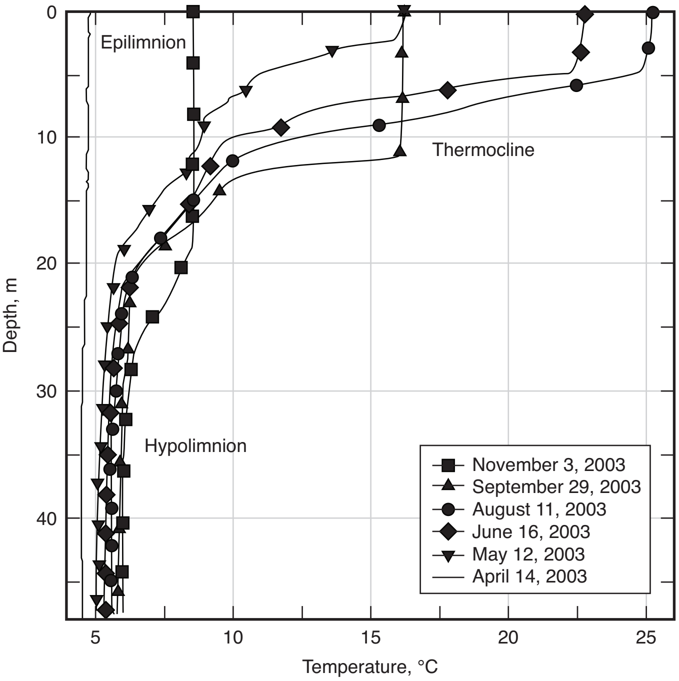


FIGURE 5.3 Temperature profiles of Lake Goitsche, Germany, at station XN5 on six dates in 2003. Symbols are added for every 16th data point to distinguish between acquisition dates.

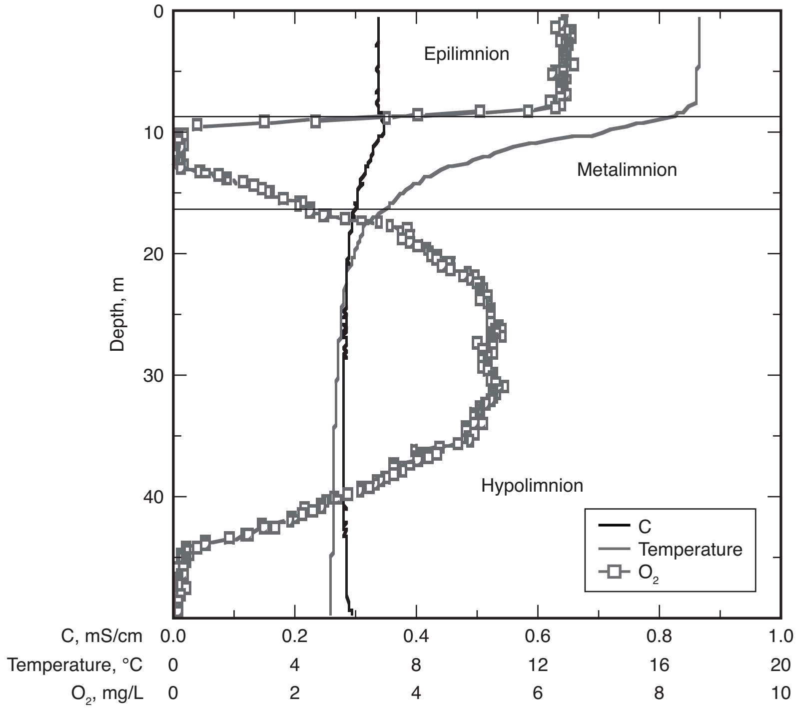
The epilimnion thickness is a crucial factor for living organisms. In general, wind determines the thickness of the epilimnion with few exceptions, such as where light penetrates beyond the mixing depth on account of wind. Empirical studies yield regressions, for example, for the epilimnion thickness (z_{epi}) in units of meters:

$$z_{epi} = 4.6A^{0.205} \quad \text{(EQ 5.1)}$$

for natural lakes in temperate regions (Patalas 1984), where higher energy input from stronger winds above larger lakes is included by surface area *A* in square kilometers. As inferred from Figure 5.3, the thickness of the epilimnion is not constant over the stratification period. In spring, a thin layer is formed, which gradually thickens over the summer on account of the cumulative input of wind energy and heat.

Because of its high gradients, the thermocline forms a special habitat. Inanimate particles can accumulate on their level of neutral buoyancy. Organisms controlling their density can position themselves in the strong-density gradient. In addition, motile organisms dwell in the thermocline, to profit from both the epilimnion and the hypolimnion. As a consequence, a layer of distinctive properties can form. Such a layer is called the *metalimnion*. Especially in nutrient-rich lakes, the decomposition of organic material can cause a depletion of oxygen, resulting in a metalimnetic oxygen minimum (Figure 5.4). On the contrary, if light can penetrate to the thermocline and photosynthesis can overcome the oxygen consumption locally, a metalimnetic oxygen maximum may occur.

In climates where the surface temperature of lakes crosses the temperature of maximum density T_{md} (i.e., 4°C for fresh water) each year, deep mine lakes (> 200 m) will be thermobarically stratified if no other processes have turned them meromictic. Such lakes show the characteristic temperature profile, which follows the T_{md} profile in the vertical over 100 or 150 m, and below a



Source: Adapted from Boehrer and Schultze 2005, with permission.

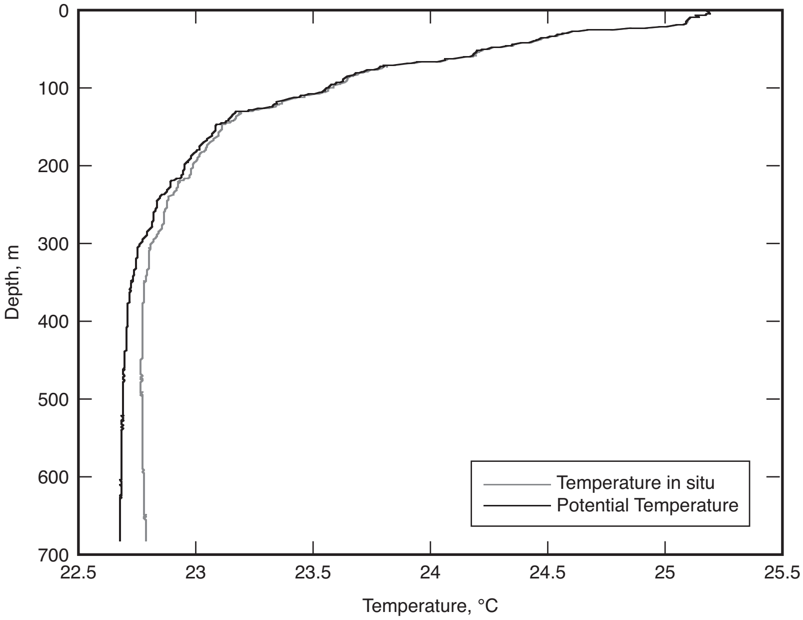
FIGURE 5.4 Profiles of temperature (T), electrical (in situ) conductivity (C), and concentration of dissolved oxygen (O_2) on September 6, 2000, in Arendsee, Germany. The boundaries between layers were drawn along the gradients in the oxygen profiles. Oxygen concentration numerically corrected for response time of 7.5 s of the sensor.

depth of 150 to 200 m temperature gradients disappear. For more details on thermobaric stratification, see Crawford and Collier (1997) and Boehrer and Schultze (2008).

Temperatures recorded in lakes are so-called in situ temperatures. Without any further annotation, temperature data will be understood as such, as it is the physically, chemically, and ecologically relevant parameter. However, for detailed considerations on the stability and vertical temperature gradients, the reference of potential temperature (*dT*/*dz*) may be useful. This quantity accounts for the energy required for expansion when a water parcel is transferred to atmospheric pressure adiabatically (*ad*), that is, without exchanging energy with the environment:

$$\left(\frac{dT}{dz}\right)_{ad} = \frac{g\alpha(T + 273.15)}{C_p} \qquad \text{(EQ 5.2)}$$

In Equation 5.2, z represents the vertical coordinate, g = 9.8 m/s^2, the Earth acceleration is the temperature-dependent expansion coefficient, and $C_p \approx 4{,}185$ J/(kg$K$) is the specific heat where K is temperature expressed in Kelvin. In lakes where the deep water is close to the temperatures of maximum density T_{md}, the thermal expansion coefficient is very small, $\alpha \approx 0$. On the contrary, Lake Malawi is located in the tropical zone of Africa with deep water temperature far from 4°C. Consequently, the difference between in situ temperature and potential temperature is noticeable. In this case, potential temperature indicates a stable stratification of the lake by temperature only, whereas a wrong interpretation of the in situ temperature profile would support the opposite conclusion (Figure 5.5).



Source: Data from Vollmer et al. 2002. Reproduction from Boehrer and Schultze 2008, with permission from American Geophysical Union.

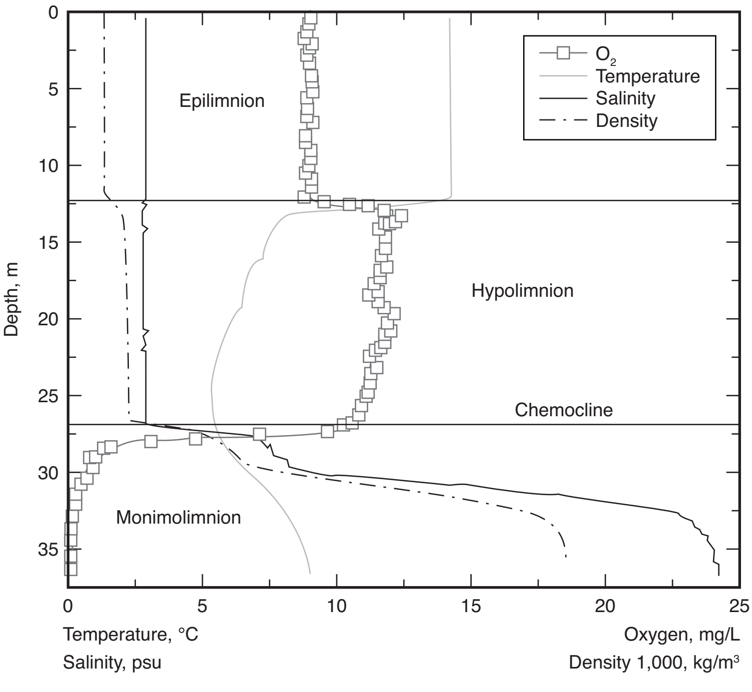
FIGURE 5.5 Profiles of (in situ) temperature T and potential temperature near the deepest location of Lake Malawi, Africa, on September 13, 1997

Salinity Stratification

The ventilated underground in the vicinity of a mine void as well as the overburden, waste rock, unlined process tailings, or ash dumps may release soluble minerals into the aquatic domain. As a consequence, mine waters in general show a higher concentration of total dissolved solids (TDS) than most freshwater systems, and concentrations in the range of 1 g/kg of mine lake water can commonly be encountered. Higher concentrations allow for higher water density gradients. In addition, substances such as iron can dissolve or precipitate because of changing conditions of oxidation–reduction (redox) potential or pH. As a consequence, density gradients can form within the water body.

Dissolved solids modify the properties of lake water. In ocean water, salinity is commonly used to describe the dissolved salt concentration (Figure 5.6). For example, 1 kg of ocean water contains about 35 g of salt; ocean water has a salinity of 35 per mil (parts per thousand). Values given in practical salinity units (psu) are calculated from measurements of electrical conductivity and temperature, and approximate the value per mil for ocean water. The evaluation is straightforward and often used if detailed information on the composition of dissolved substances is missing. Brackish water, that is, water mixed from sea water and fresh water, shows a similar composition of dissolved substances as the ocean, whereas salt composition in lakes can greatly deviate from ocean conditions. In such cases, salinity is better replaced by TDS in the limnic environment.

General approximations for the relation between electrical conductivity, temperature, pressure, and density have been developed for fresh water (Chen and Millero 1986). These approximations are restricted to a maximum TDS concentration of 600 mg/kg lake water. Such



Source: Data from Boehrer and Schultze 2008.

FIGURE 5.6 **Profiles of temperature, salinity, dissolved oxygen, and density from Rassnitzer See in the former mining area of Merseburg-Ost (Germany) on October 7, 2003. Oxygen concentration numerically corrected for response time of 7.5 s of the sensor.**

approaches assume that substances which contribute considerably to density can be detected by electrical conductivity. This is not valid for many organic substances (e.g., humic substances), weak acids (e.g., silicic acid), and suspended matter (e.g., suspended metal oxyhydroxides).

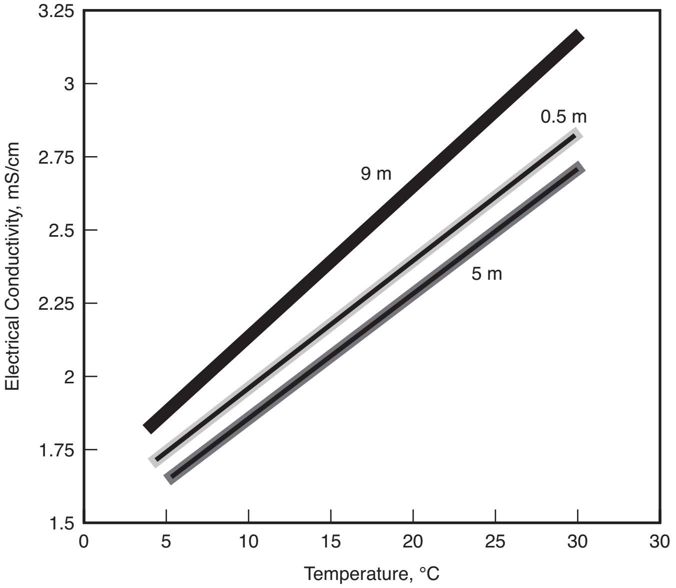
The electrical conductivity of a water parcel is temperature dependent. The term *electrical conductance* $\varkappa_{25}$ is used for the electrical conductivity at a reference temperature of 25°C. Electrical conductance is influenced by chemical composition. Figure 5.7 shows the temperature dependence of electrical conductivity for three different water samples from the same lake.

For detailed considerations on the stratification in pit lakes with highly variable compositions and concentrations, it is strongly recommended to develop site- and time-specific relationships between temperature, electrical conductivity, and density (e.g., Schimmele and Herzsprung 2000). Only rough estimations can be gained from freshwater or ocean water approximations.

The stability of a water column is quantified by the density increase in the vertical dimension according to

$$N \leq = -\frac{g}{\rho}\frac{dp}{dz} \qquad \text{(EQ 5.3)}$$

where g is the acceleration on account of gravity, ρ is density, and z is the vertical coordinate. N is called the stability frequency or Brunt-Väisälä frequency (unit 1/s), which indicates the maximum frequency (ω) for internal waves that can propagate in the respective stratification. The parameter N^2 indicates how much energy is required for the exchange of water parcels in the vertical direction. As vertical excursions in layers of high stability require more energy, it has been found that turbulent transport through such strongly stratified layers is comparably small.



Source: Adapted from Karakas et al. 2003.

FIGURE 5.7 Electrical conductivity of three water samples of Mining Lake 111 versus temperature. Gray symbols represent the measured conductivity; the solid line shows the linear regression.

MEROMIXIS

In some lakes, concentrations of dissolved substances raise the density of the deep waters enough that they do not participate in the total overturn during the annual cycle. Such lakes are termed *meromictic* or permanently or perennially stratified. The chemically different bottom layer is called *monimolimnion*, whereas the water body above is called the *mixolimnion*. In many meromictic lakes, deep circulation erodes the monimolimnion, leaving a sharp gradient at the end of the circulation period. The transition of all water properties between the mixolimnion and the monimolimnion can happen within a few decimeters (see Figure 5.6). This sharp gradient is called *halocline*, *chemocline*, or *pycnocline* to indicate whether the change in properties is due to salinity, chemical gradient, or density gradient, respectively.

Processes Eroding Meromixis

Wallendorfer See in Germany is a salinity-stratified lake in which the vertical position of the halocline was precisely recorded over several years (Figure 5.8). While artificial tracers guaranteed that the groundwater connection only contributed a small part to the vertical shift of the halocline, most of its vertical displacement was attributed to the turbulent erosion during seasonal mixolimnion overturn. On average, the highly saline monimolimnion (80 g/kg) lost 14 cm per year to the less saline (about 5 g/kg) mixolimnion (Figure 5.8, and von Rohden 2002). This small amount is a consequence of the extremely high density difference (about 50 kg/m^3) between monimolimnion and mixolimnion. In lakes with less density difference, faster erosion would be expected.

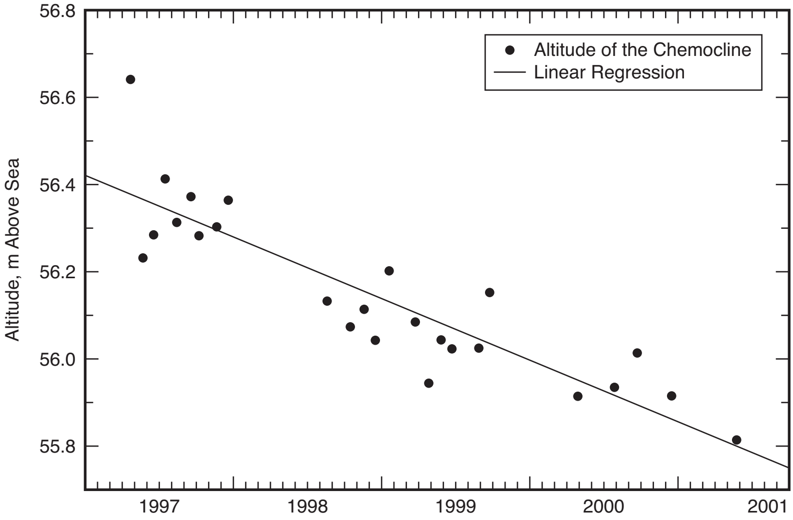
During the stratification period, dissolved substances are transported through the water column by turbulent diffusive processes. Observations of the spreading of an artificial tracer cloud in the monimolimnion of Rassnitzer See (in mining complex Merseburg-Ost, Germany), verified a strong correlation of vertical transport coefficients and stability caused by the density gradient (see Figure 5.9). This indicates that high density gradients (large N^2) limit the vertical transport.

The most prominent source of kinetic energy in a lake is wind, which applies a stress to the water surface. Waves and currents form that cause friction at the lake boundaries and internal current shear. Both effects eventually lead to instabilities and turbulence. Turbulent mixing carries dissolved substances through the water column much faster than molecular diffusion. Consequently, meromixis can preferably be encountered in lakes that are sheltered from the wind, such as lakes with small surface areas, or lakes surrounded by forest or steep side walls of a pit, or lakes that have deep depressions in the lake bed, which are less affected by lakewide currents.

Processes Sustaining Meromixis

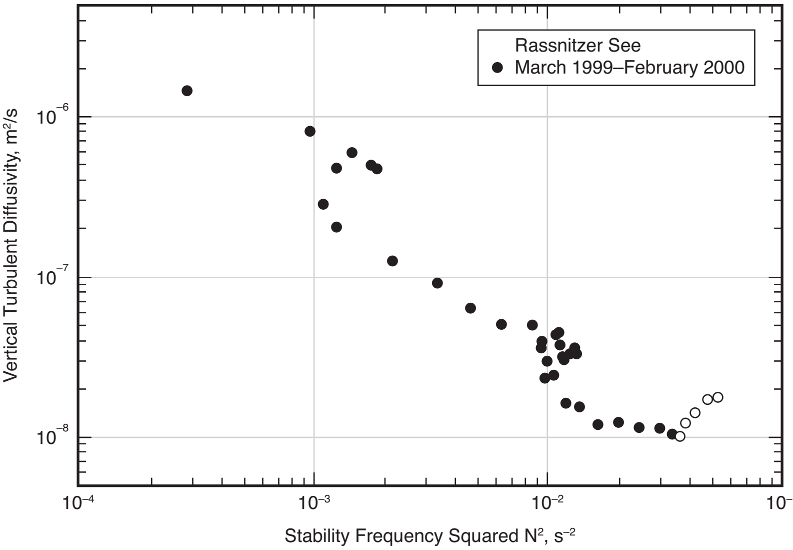
Meromixis will only persist if a process is present that sustains the density gradient. If factors outside of the lake control the gradient, it is called *ectogenic meromixis*; the special case of groundwater is referred to as *crenogenic meromixis*. If the gradient is controlled by factors within the lake, which cause the transport of dissolved substances upgradient, from the mixolimnion to the monimolimnion, then the system is referred to as *endogenic* or *biogenic meromixis*, because biology or microbiology control decisive processes.

If a void is filled from sources of different water quality, density differences may be high enough to form meromixis. After decommissioning, the 330-m-deep Island Copper mine pit (Vancouver Island, British Columbia, Canada) was filled with ocean water and capped with a 7-m-thick freshwater layer. It was designed to be meromictic to dispose of and confine mining influenced water (MIW) to the deep monimolimnion waters (Fisher and Lawrence 2006). Similarly, above-mentioned pit lake Rassnitzer See (Figure 5.6) in Germany remains meromictic because of saline



Source: Adapted from von Rohden and Ilmberger 2001.

FIGURE 5.8 Altitude of the chemocline in pit lake Wallendorfer See, Germany, measured at site MA2, over the years 1997 to 2001



Source: von Rohden and Ilmberger 2001, with permission of Birkh□user Verlag.

FIGURE 5.9 Turbulent diffusive transport of an artificial tracer in pit lake Rassnitzer See, Germany, versus density gradient, $N^2 = -g/\rho \, d\rho/dz$. Full circles: measurements inside the monimolimnion; open circles: measurements in the chemocline.

groundwater inflows from a deep aquifer. Inputs of MIW maintain the meromixis in South mine pit in Copper Basin, Tennessee, United States (Wyatt et al. 2006), and in the natural Camp Lake in Manitoba, Canada (Moncur et al. 2006).

Biogenic meromixis originates from organic material decomposing in the deep water of a lake. Organic material, referred to as CH_2O in the following equations, is formed in the epilimnion by photosynthetically active plankton:

$$CO_2 + H_2O \xrightarrow{\text{Light}} CH_2O + O_2 \qquad \text{(EQ 5.4)}$$

or it is carried in by inflowing streams (i.e., allochthonous material). A portion of this material settles. Its decomposition is facilitated by the presence of oxygen or other oxidizing agents (e.g., nitrate, ferric iron, or sulfate) and bacteria:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \qquad \text{(EQ 5.5)}$$

The end products partly dissolve in the deep layers of the lake and locally raise the water density.

In meromictic mine lakes, decomposition of organic material coupled with iron cycling is often found:

$$CH_2O + 4Fe(OH)_3 + 8H^+ \rightarrow CO_2 + 4Fe^{2+} + 11H_2O \qquad \text{(EQ 5.6)}$$

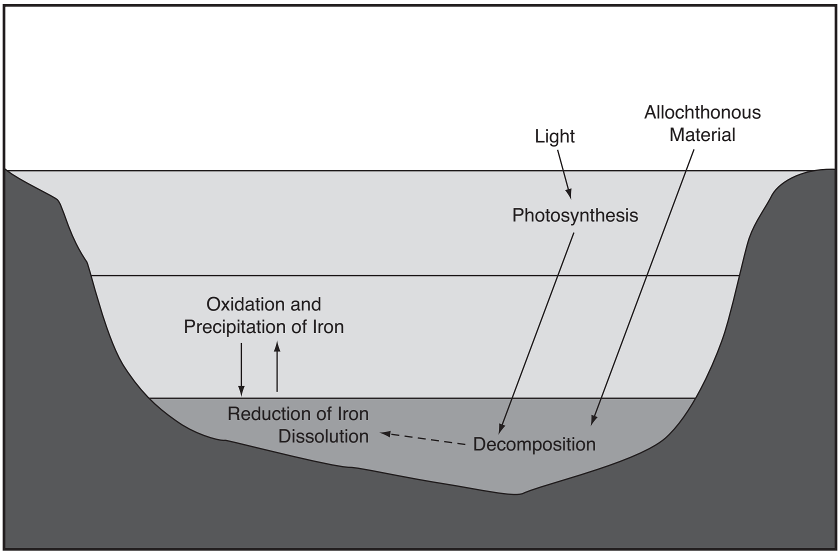
Diffusive and turbulent diffusive transport processes carry ferrous iron and oxygen into the chemocline. Should this ferrous iron get into contact with oxygen, it becomes oxidized and precipitated as ferrihydrite (Figure 5.10):

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O \qquad \text{(EQ 5.7)}$$

$$Fe^{3+} + 3H_2O \rightarrow 4Fe(OH)_3 + 3H^+ \qquad \text{(EQ 5.8)}$$

Ferrihydrite settles downward and reenters the monimolimnion. As a consequence, ferric iron is made available for the decomposition of organic material in the monimolimnion again. Hongve (1997) described this cycle in detail for natural meromictic lakes. Both oxidation and reduction are facilitated by the presence of microbial organisms. Reactions 5.7 and 5.8 in sequence release protons, causing the formation of local pH minima in the contact zone between oxic and anoxic layers.

A similar cycle between oxic and anoxic zones can be accomplished by manganese. Also denitrification, sulfate reduction, and methanogenesis are involved in decomposing organic material (Wetzel 2001; Schlesinger 2005). In addition, the calcite cycle has turned natural lakes meromictic (Rodrigo et al. 2001).



Source: Adapted from Boehrer and Schultze 2008.

FIGURE 5.10 Oxidation of ferrous iron to ferric iron and consequent precipitation in oxic layers of the lake. In the monimolimnion, the reduction to ferrous iron is facilitated by using organic material as a reduction agent. Diffusion across the chemocline and mixing of mixolimnetic waters with monimolimnetic waters is very inefficient in terms of transport of iron, as iron is oxidized and precipitated out of the oxic layer.

CONSEQUENCES OF STRATIFICATION FOR WATER QUALITY

Seasonal Stratification

During stratification, the exchange of dissolved substances between hypolimnion and epilimnion is limited. Only turbulent diffusive processes and the gradual thickening of the epilimnion during stratification transport dissolved substances between both layers. On the contrary, sedimentation continuously removes substances from the epilimnion. If substances are redissolved from the sediment or if they are liberated during sedimentation through the hypolimnion as a result of microbial decay of organic matter, they may accumulate in the hypolimnion during the stratification period. The highest concentrations usually occur just above the sediments. The described processes are accompanied by oxygen consumption and may eventually lead to anoxia in the hypolimnion. Anoxia may act as an additional driver for the redissolution of substances from the sediment (e.g., phosphates).

Also, groundwater entering the hypolimnion may contribute to the accumulation of dissolved substances and to oxygen consumption by introducing sulfate and ferrous iron. Chemical transformations during passage of groundwater through the lake sediment must be kept in mind (see Blodau 2004, 2005).

Most commonly, ferrous iron, phosphate, hydrogen sulfide, and reduced species of toxic trace elements (e.g., arsenite, AsO_3^{3-}) and heavy metals can be enriched in deep waters. As hydrogen sulfide and heavy metals precipitate as metal sulfides, they do not coexist at high concentrations at neutral pH. During seasonal circulation, anoxia and accumulated substances are removed by further distribution or oxidation and chemical precipitation.

Meromixis

Meromixis limits the vertical transport through the water column. Dissolved substances can be accumulated over several years or even decades or centuries. In monimolimnia, much higher concentrations are encountered than in hypolimnia. Without considerable import of oxygen, monimolimnia usually show anoxic conditions. Reductive processes are facilitated by parallel oxidation reactions, many involving organic matter. Madison et al. (2003) observed pyrite oxidation in the anoxic monimolimnion of the Berkeley pit lake, Montana (United States). Ferric iron, settling from the oxic mixolimnion and redissolved under the monimolimnetic conditions, oxidized remaining pyrite in the side walls inside the monimolimnion. This process was found to contribute considerably to the acidity budget of the monimolimnion and the whole lake. This process may occur also in other pit lakes. From observations it is known that chemoclines can provide zones of intensive colonization with only few species. Obviously, some plankton species take advantage of such gradients (Tonolla et al. 2004) as observed in Mine Lake 111 and Waldsee near Döbern, Germany (Rücker et al. 1999).

Permanently exposed to the hydrostatic pressure, gases (CO2 [carbon dioxide], H2S [hydrogen sulfide], and others) can accumulate in concentrations far beyond concentrations encountered in mixolimnia. Murphy (1997) made some predictive calculations about whether a limnic eruption (a sudden release of the accumulated gas) can happen in pit lakes. He found that such an event is not very likely but cannot be excluded. None of the theoretical considerations attempting to explain the eruption of Lake Nyos (Africa; Kling et al. 1987) has received wide acceptance. As a consequence, there is no definite answer why some lakes with oversaturated monimolimnia can produce limnic eruptions and others degas quietly. Extreme storms, turbidity currents accompanying flood events, or big landslides at the lakeshore may produce a sudden partial or total overturn of a meromictic pit lake. The consequences for lake water quality may be dramatic and include fast depletion of oxygen or total anoxia, distribution of accumulated toxic substances over the whole water body, or an internal pulse of eutrophication by nutrients formerly accumulated in the monimolimnion.

OPTIONS TO INDUCE OXIC CONDITIONS IN HYPOLIMNIA AND EFFECTS ON WATER QUALITY

Holomixis can be fostered by minimizing wind sheltering (e.g., deforestation of lakeshore), backfilling deep depressions in the lake bed and removing obstacles for lakewide circulation, such as shallow sills. Hypolimnetic water can also be pumped from the lake before dissolved concentrations become a real concern. Artificial destratification/circulation technologies exist that release dissolved gases stored at great depth. The rising bubble plume lifts cool hypolimnetic water to the surface. Such technologies are well established in lake restoration (Cook et al. 2005).

Probably the most undesired consequences of stratification are oxygen depletion and accumulation of nutrients and toxic substances in deep water. Hypolimnetic aeration/oxygenation is a well-established strategy to prevent or remove anoxia. Small bubbles of oxygen are pushed into the deep water, where they dissolve completely. Alternatively, water is withdrawn from the deep water and after oxygen addition returned to the lake. Stratification can be conserved, and, consequently, the undesirable distribution of substances (e.g., nutrients, ferrous iron, and hydrogen sulfide) over the whole lake is avoided (Cook et al. 2005).

Removal of potentially dangerous substances may be performed by chemical precipitation. The required chemicals should be spread only in the part of the water body where dangerous substances are located. Apparatuses primarily developed for hypolimnetic aeration may be used for such purposes (Koschel et al. 2001) as well as submerged spreaders tracked by boats. Ferrous iron can remove hydrogen sulfide, and ferric iron combined with alkaline substances (e.g., lime, soda ash, combustion ashes) may be used to flocculate toxic trace elements or phosphate.

OPEN QUESTIONS

Although stratification and circulation of lakes has been investigated for more than 100 years and models have been applied for about 30 years, the quantitative prediction of chemical stratification remains a challenge (see Tables 5.1 and 5.2). There is no single model currently available that covers the whole complexity of stratification and circulation of pit lakes and the variability and interaction of the relevant factors, such as hydrology of the lake, morphology of the lake basin, exposure to wind, climatic conditions, water quality of inflows, and biogeochemical reactions in the lake water and lake sediment and its coupling back on lake stratification.

Detailed and accurate field studies are needed to further develop and validate models. In particular, the quantitative description of meromixis by models must be improved. Field studies have been conducted at many places, but these data and the results are not easily accessible to the scientific engineering community in all cases. Good documentation of all environmental factors and proper scientific publication would form a valuable contribution for the further promotion of predictive modeling. Beyond this, quantification of chemical transformations and their impact on density stratification still require further research projects to ultimately facilitate predictive modeling for cases of meromixis.

TABLE 5.1 Case studies on stratification and circulation in pit lakes

Pit Lake Name, Location	Reference
Berkeley Lake, Montana, United States	Gammons and Duaime 2006
Blackhawk, Blowout and Duncan, Utah, United States	Castendyk and Jewell 2002
Brenda, British Columbia, Canada	Stevens and Lawrence 1998
East Sullivan Lakes, Quebec, Canada	Tass□ 2003
Goitsche, Germany	Boehrer et al. 2003
Island Copper mine, Vancouver Island, Canada	Fisher and Lawrence 2006
Merseburg-Ost (Rassnitzer See, Wallendorfer See), Germany	B□hrer et al. 1998
Mine Lake 111, Germany	Karakas et al. 2003
Yerington, Nevada, United States	Jewell and Castendyk 2002
Martha mine, New Zealand	Castendyk and Webster-Brown 2007a, 2007b

TABLE 5.2 General papers on stratification and circulation in pit lakes

Title	Reference
Difficulties in predicting the permanent stratification of open cast mining lakes	Boehrer 2000
On the relevance of meromixis in pit lakes	Boehrer and Schultze 2006
Stratification of lakes	Boehrer and Schultze 2008
Pit lakes: their characteristics and the potential for their remediation	Castro and Moore 2000
Physical limnology of existing mine pit lakes	Doyle and Runnels 1997
Mixing mechanisms in lakes	Imboden and W est
The motions of lake water	Imboden 2004
Physical properties of water relevant to limnology and limnetic ecology	Reynolds 2004
The effect of subaqueous disposal of mine tailings in standing waters	Stevens and Lawrence 1997

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