

## Acidic Pit Lakes

The Legacy of Coal and Metal Surface Mines

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## Chapter 2

# Terrestrial Environment of Pit Lakes

### 2.1 Morphology, Age, and Development of Pit Lakes

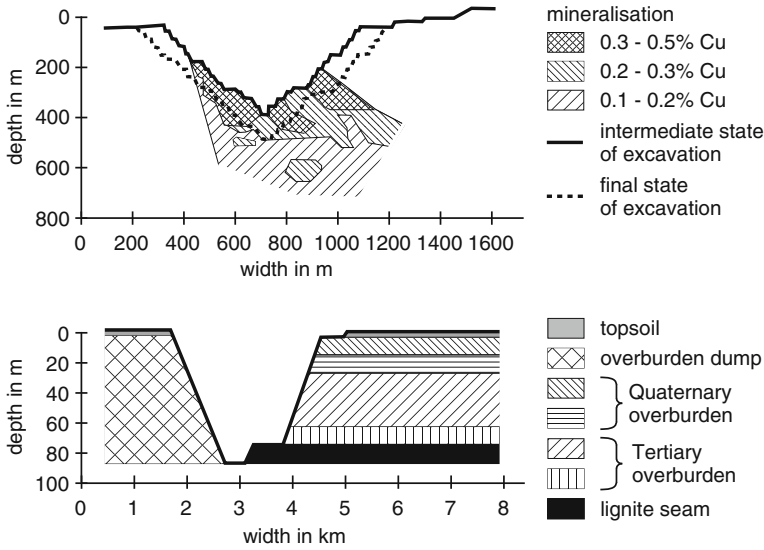
Martin Schultze, Bertram Boehrer and Walter Geller

Several factors determine the shape of a mine pit at the time of decommissioning. The most important of these are the amount and distribution of coal, lignite, or ore in the ground and the stability of the surrounding material, which forms the side walls of the pit after closure. Other factors that play a role are backfilling (if it occurred), material movement and erosion, and the age of the pit lake.

In the case of steeply dipping ore veins, the open cast mine follows the veins from surface to depth. This is typical for many open cast metal mines. Coal and lignite deposits usually have a different shape since they originated from a horizontal deposit. The seams are confined by surrounding strata and extend horizontally (unless the strata have been folded or faulted) over wide areas. These deposits are often exploited by strip mining. Both types are illustrated in Fig. 2.1. Some mines may show features of both types.

The steepness of the side slopes of a decommissioned mine depends on the stability of host rock and overburden. Sidewalls of a mine in a hard rock environment can be designed at a steep angle, but slopes of much smaller inclination are mandatory in unconsolidated rock. Figure 2.1 illustrates this. Hard rock allows for steeper slopes not only during mining but also when a pit has been filled with water to form a lake, since hard rock walls are less susceptible to erosive wave action. Unconsolidated rock, however, are eroded rapidly by wave action. If the slopes of a mine void are not well prepared for wave action, this may result in permanent shore erosion and even in landslides.

Consideration of long term stability extends beyond the period of mining, to when a different hydrological setting has changed the boundary conditions. Cohesion of unconsolidated rock decreases when the underground fills with water. Landslides of enormous horizontal and vertical dimensions (Fig. 2.2) can result (Nestler and Stoll 2001). Where the rising groundwater meets the surface, springs



**Fig. 2.1** Typical examples of open cast mines: *upper panel* from metal mining in solid rock, based on conditions at the Aitik mine in northern Sweden, with simplifications; *lower panel* from lignite mining in Germany, where seams are usually embedded in unconsolidated rock like gravel, sand, loam, and clay (based on conditions at the former mine Espenhain, with simplifications); note the different scales of the panels

can form, and the flowing waters can destroy the side walls. In addition, groundwater flow exerts pressure against the slope from the underground into the mine void and causes suffusion (transport and removal of smaller particles). Clay layers and fractures dipping into the mine void or earthquakes can also promote landslides. Some of these issues can be handled more easily when the water table inside the mine pit is raised rapidly by introducing water, e.g. by river diversion. Consequently, the filling procedure also influences the final shape of a pit, at least in cases of unconsolidated rock.

The steepness of a lake basin, i.e. the initial mine void, can be expressed by the relative depth,  $z_{\text{rel}}$ , which is defined as the ratio of the maximal depth of a lake  $z_{\text{max}}$  to the mean diameter of the lake surface  $A$ , often expressed in percent (Wetzel 2001):

$$z_{\text{rel}} = \frac{z_{\text{max}} \times \sqrt{\pi} \times 100\%}{2 \times \sqrt{A}} \quad (2.1)$$

Figure 2.3 illustrates differences between pit lakes in former lignite mines in Germany, former coal mines in Western Australia, and former metal mines. While the German lignite pit lakes are embedded in unconsolidated rock (gravel, sand, loam, and clay), requiring small slope inclinations, most pit lakes in former metal mines are embedded in solid, often crystalline rock (e.g. Dallmeyer and Martinez



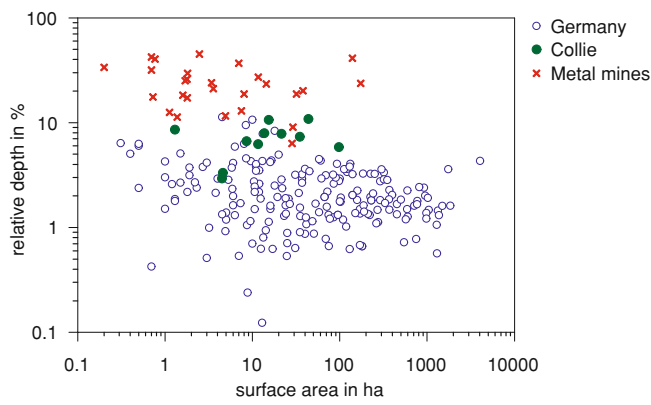
**Fig. 2.2** Landslide of dumped overburden in the former Spreetal Mine (Lusatian lignite mining district, Germany) at October 12, 2010. The ground broke over an area of ca. 1800 m × 600 m (ca. 110 ha), damaging the neighbouring pit lake (*upper margin of the photo*). It was caused by an initially local liquidation of deeper parts of the overburden dump and supported by extremely high water saturation of the entire dump as a result of a very rainy period of about 10 weeks. (Photo: Radke, LMBV)

Garcia 1990), allowing steep slopes. The pit lakes of the Collie Basin (Western Australia) are embedded in sandstone, mudstone, and shale (Le Blanc Smith 1993), resulting in an intermediate position regarding the relative depth (Fig. 2.3).

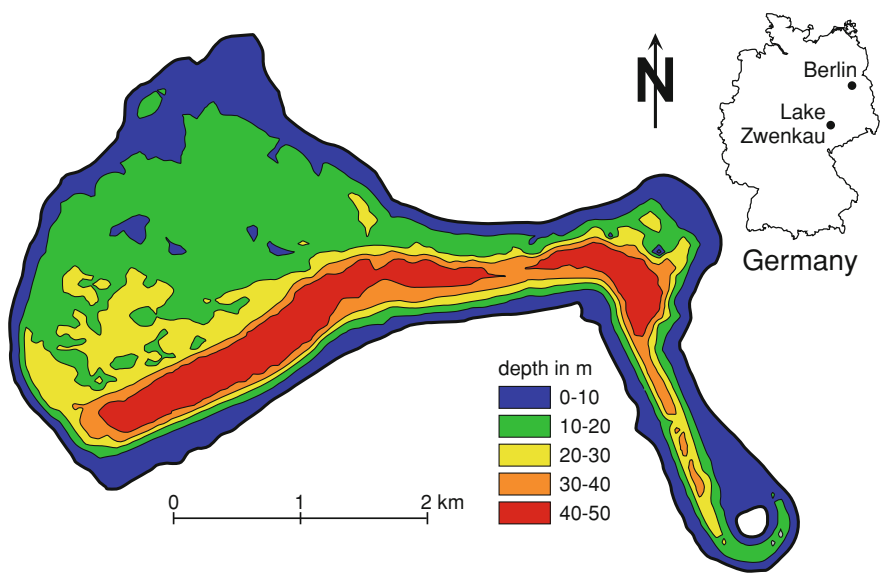
Backfilling of the mine void with overburden and waste rock will change the morphometry of a pit. Backfilling is common in strip mining, where overburden is deposited in areas where the coal has been previously excavated (Fig. 2.1, lower panel). Large strip mining technology, e.g. the conveyor bridge shown in Fig. 1.1 (see Chap. 1), can leave a narrow, deep trench as a final void. Many pit lakes of this type resemble a long, deep graben, often accompanied by large, shallow areas where extended stands of macrophytes may develop (Fig. 2.4).

In contrast, a mine that proceeds more vertically may not have space for dumping as long as mining is proceeding (Fig. 2.1, upper panel), but backfilling after decommissioning is typically too expensive. As a consequence, backfilling in open cast metal mines is unusual. The Aznalcollar pit lake (Spain) is an example for partial backfilling with waste rock from a neighbouring open cast mine (Schultze et al. 2008).

The available material for backfilling is limited by the removal of the exploited material. Coal and lignite are used for combustion. The residual ash has a much smaller volume, and depending on the contaminants it contains, it is often too toxic for placement in permeable mine spoil. Therefore, complete backfilling to the initial contour of the landscape would appear to be impossible. However, overburden material that has been fragmented takes up more space than it did before it was disturbed. This is often referred to as ‘swelling’; at many coal mines where the



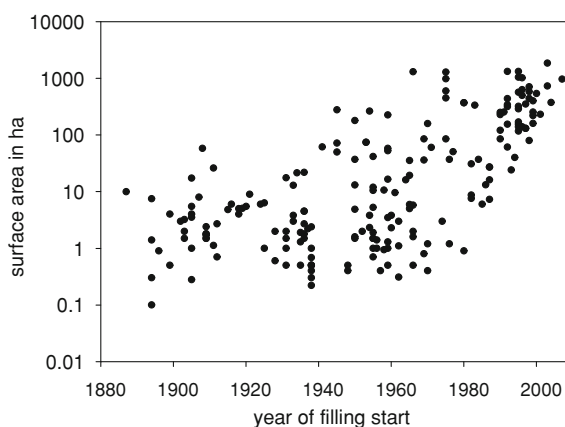
**Fig. 2.3** Plot of the relative depth of German pit lakes in former lignite mines (database identical to the one used in case study 5.1), pit lakes in the Collie coal basin in Western Australia (database: McCullough et al. 2010), and pit lakes in former metal mines (database: Crusius et al. 2003; Doyle and Runnels 1997; Fisher and Lawrence 2006; Levy et al. 1995; Lu 2004; Lyons et al. 1994; Park et al. 2006; Sánchez-España et al. 2008; Steven and Lawrence 1997; Wyatt et al. 2006)



**Fig. 2.4** Bathymetric map of Lake Zwenkau (Central German lignite mining district)

volume of overburden greatly exceeds the amount of coal extracted, this swelling more than makes up for the amount of material removed, and no pit lake forms. This commonly occurs in the eastern U.S.

**Fig. 2.5** Surface areas of German pit lakes in former lignite mines relative to the age of the pit lakes, reflecting the increased performance of mining equipment (database identical to that used in case study 5.1)

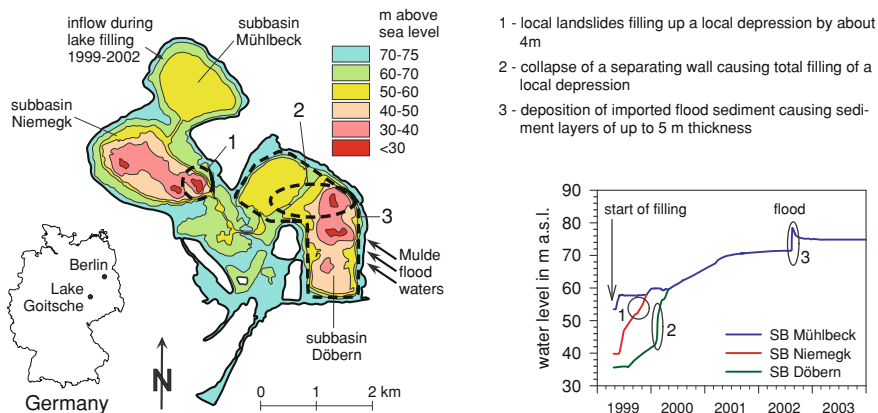


Pit lakes have formed since the end of the nineteenth century, e.g. in Germany. At that time, open cast mines were limited by the performance of the available mining equipment. Consequently, the resulting pit lakes were small, i.e. less than 1 ha surface area with a maximal depth less than 10 m. As mining equipment became more powerful, extraction depths and areas grew. Today, opencast mines and resulting pit lakes have surface areas of several square kilometres and depths of several hundreds of meters. Therefore, there is a correlation between age of pit lakes and their size (Fig. 2.5).

After a lake has formed, its morphometry is subject to changes due to sedimentation: the older the pit lake, the thicker the accumulated sediment at the lake bottom resulting from chemical precipitation, dead plankton, erosion of the shore, and allochthonous sediment input by streams or rivers feeding the pit lake. In unconsolidated rock, the sedimentation rate may be very high during filling and in the first years after filling, until the formation of the lake shore has reached equilibrium with the mean local wave action. Without landslides, however, sedimentation only changes the morphometry at a slow pace. Wagner (2010), for example, found that ca. 500 m<sup>3</sup>/a of sand and finer material was transported along the shore of Lake Cospuden (4.3 km<sup>2</sup> surface area) by wind-driven surface waves and the resultant erosion of the shoreline.

To close this section, we introduce Lake Goitsche (Germany; Fig. 2.6) to illustrate different factors that influence the shape of the lake basin, including changes in morphometry caused by landslides and flooding. Lake Goitsche consists of three subbasins, named Mühlbeck, Niemeck, and Döbern, respectively (Fig. 2.6). The lake was formed by deviating water from the nearby Mulde River into the Mühlbeck subbasin. Subbasins Niemeck and Döbern were subsequently filled when the water overflowed into them (see Fig. 2.6, right panel).

The geology of the deposit created two islands in the central southern part of the lake and a sill north of them. They are the result of a paleo-dune, which resulted in the local absence of lignite. Consequently, the area of the current islands was not mined. The deepest locations of the lake basin result from local depressions in the



**Fig. 2.6** Changes of morphoplogy in Lake Goitsche (Germany). *Left panel* Bathymetric map of Lake Goitsche showing the initial morphology of the lake basin at the start of filling in May 1999. The *dotted lines* indicate the regions within the lake basin where the morphologic changes occurred. *Right panel, upper part* Details of the morphologic changes. The numbers 1, 2, and 3 correspond to the spatial indication of morphologic changes in the *left panel* and to the temporal occurrence of the changes in the diagram in the *lower right panel*

lignite seam caused by the dissolution of salt deposits deeper underground (see Fig. 5.2 in case study 5.1).

The excavation technology and the spatial progress of the exploitation are the reasons for the shallow water depth in the western part of the Döbern subbasin and for the peninsula separating the Mühlbeck and Döbern subbasins. Both areas were used as dump sites for overburden in the final phase of mining. The mining started west of subbasin Niemeck, and initially proceeded southward. River Mulde initially crossed the eastern part of the current Lake Goitsche (mainly in the northern part of subbasin Döbern and the area between subbasins Mühlbeck and Niemeck). After diversion of the river, mining proceeded eastward in a northern and southern arc, in parallel, like a pincer. The subbasins Mühlbeck and Niemeck were not used as dump sites for overburden to allow later exploitation of amber deposits, which lie beneath the lignite seam in the area of these two subbasins (Wimmer et al. 2006).

During remediation, landslides and a flood produced further changes in the basin morphology. First, small-scale sediment transport and landslides near the former deepest point of the pit (the southwestern part of subbasin Niemeck; number 1 in Fig. 2.6), reduced the maximum depth in this area by about 4 m as this subbasin was filled (Boehrer et al. 2003). Then, when water started to spill from subbasin Niemeck into Döbern, the separating wall broke and much of it was flushed into Döbern and filled some deep areas in the northern part of the subbasin (number 2 in Fig. 2.6). Finally, an extreme event happened when the catchment of the nearby Mulde River received extremely high precipitation in summer 2002, causing record river water levels (Klemm et al. 2005). The flood water found a

way into Lake Goitsche and created a river bed (about 1 km long, 100 m wide, and up to 5 m deep). About  $100 \times 10^6 \text{ m}^3$  of flood water entered the lake in less than 48 h, carrying a load of about  $1 \times 10^6 \text{ m}^3$  of suspended material into the lake. Most of this suspended material settled in the quieter waters of the lake. This changed the morphometry of the lake by up to 5 m over a considerable area (number 3 in Fig. 2.6; Boehrer et al. 2005).

Although the amount of such displaced material is small compared to lake volume (e.g.  $109 \times 10^6 \text{ m}^3$  in Lake Cospuden,  $213 \times 10^6 \text{ m}^3$  in Lake Goitsche), local depressions of a lake bottom can be filled and bathymetric maps of the anticipated morphology of the lake bottom, based on the final measurements of the mine surveyors before lake filling, will become inaccurate. In addition, erosion and landslides are accompanied by an intense washout of substances into the lake water, which can have considerable influences on the progress of neutralization processes (e.g. Schultze et al. 2002).

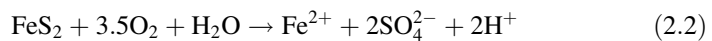
## 2.2 Influence of Groundwater on Pit Lakes

### Martin Schultze

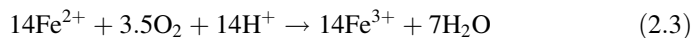
Surface mining for coal, lignite, and metals requires the total dewatering of the mined portion of the ground down to the deepest level of the mine. The hydraulic head of the groundwater below the surface mines has to be lowered, at least enough to prevent a dangerous uncontrolled inflow of groundwater through the bottom of the mine. Therefore, groundwater cones of depression form around the surface mines, as schematically shown in Fig. 2.7. The depression cone results in a groundwater flow to the mine from all directions.

The formation of the cone of depression exposes strata that were saturated with water to atmospheric oxygen. If the strata contain pyrite, it will begin to oxidize, producing acidity, sulfate, and dissolved iron, according to the Eqs. 2.2–2.5:

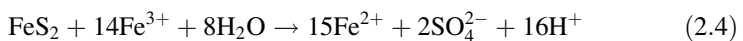
Oxidation of pyritic sulfur by oxygen



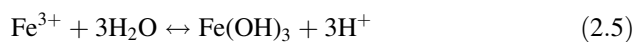
Oxidation of ferrous iron by oxygen



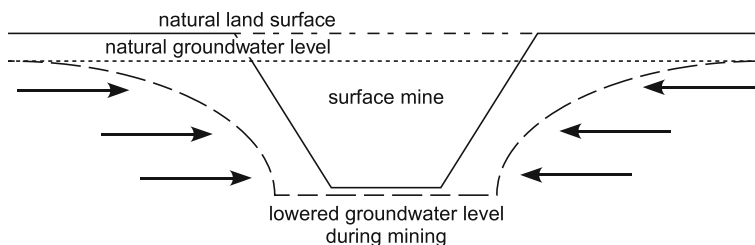
Oxidation of pyritic sulfur by ferric iron



Ferric iron that was not consumed by further oxidation of pyritic sulfur, hydrolyses and precipitates if the pH is above 3.5, according to the following reaction:







**Fig. 2.7** Schematic cross section of a surface mine showing the groundwater levels before mining and during mining. The *arrows* indicate the flow direction of the groundwater under the conditions of mining

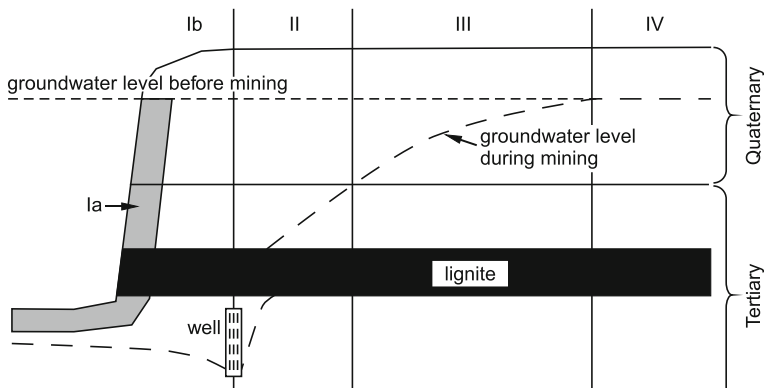
Often, other sulfide minerals are present, in addition to pyrite. At many metal mines, these other sulfide minerals are the target of the mining operations. They are also subject to oxidation and can contribute to acidification and water contamination.

The acidity reacts with other minerals that are present. This consumes a portion of the acidity and buffers the pH. The most important reactions are the consumption of dissolved bicarbonate, the dissolution of carbonates, silicates, metal hydroxides, and oxides, and ion exchange. Diverse ions, including aluminum, are mobilized, which causes many mine waters to be highly mineralized.

As long as the pyrite oxidation occurs underground, the availability of oxygen is limited. Therefore, not all of the dissolved iron is oxidized. The remaining ferrous iron represents hidden (mineral) acidity, which becomes relevant when the groundwater enters a pit lake or reaches the surface at springs and is exposed to higher oxygen concentrations.

This has to be considered when analyzing groundwater from mining-influenced sites and when interpreting the results. An initial oxidation step is recommended for the titrimetric determination of acidity and in order to prevent any misunderstanding, the procedure used to determine acidity should be clearly described (Kirby and Cravotta 2005a, b). A clear description of the analytical procedure used is even more important if the acid neutralization potential of the solid material along the flow paths of the water is to be considered (e.g. Morin and Hutt 2009). An accurate determination of acidity is an essential and powerful input for assessment and for planning remedial measures (e.g. Castendyk and Webster-Brown 2007; Kringel et al. 2000; Schöpke 2008).

Everything described so far applies to mines in both solid and unconsolidated rock. However, there are important differences between solid and unconsolidated rock regarding the flow of water and the interaction between air, water, and rock. In solid rock, water flow is restricted to faults, fractures, and fissures. In unconsolidated rock, the water also flows through the pore space. The interface between the fluid and the solid phase is usually much larger in unconsolidated rock than in solid rock.



**Fig. 2.8** Scheme of the concept of zones of different duration of mining related aeration of the underground in the vicinity of surface mines (modified from Grützmaier et al. 2001; for details on the characteristics of the zones see text)

A larger interface allows for more intense and faster interaction, including pyrite oxidation and dissolution of carbonates and feldspars.

Many publications on the influence of mining on groundwater exist. The following literature can be recommended for information on the relevant processes, including the long-lasting effects after mine closure: Grützmaier et al. 2001; McLemore 2008; Niccoli 2009a, b; Wisotzky and Obermann 2001; Wolkersdorfer 2008; Younger et al. 2002.

The spatial and temporal extent of aeration of pyritic material is one of the main factors influencing the amount of acidity formed during mining. Pyrite oxidation proceeds as long as pyrite, oxygen and humidity are available. After the dewatering of a surface mine ceases, the groundwater rebound usually reaches the underground areas closest to the remaining mine void later than areas that are further away. This led to classifying the underground in the vicinity of surface mines into zones based on the extent of groundwater lowering (Grützmaier et al. 2001). The concept was developed at German lignite mines where the Tertiary lignite seams are embedded in Tertiary and overlain by Quaternary unconsolidated rock. Figure 2.8 shows a schematic depiction of this concept.

The zones of groundwater lowering are characterized as follows for the typical hydrogeological conditions in German lignite strip mines (Grützmaier et al. 2001):

- Ia the side walls and the bottom of the mine void below the pre-mining groundwater level with intensive contact with oxygen for a long period
- Ib fully drained underground areas between zone Ia and the dewatering wells
- II area where the Tertiary material below the lignite remained saturated except for a small cone of depression close to the wells and the Tertiary materials above the lignite was only drained partially, while the Quaternary material was fully drained

III area where the Tertiary material remained saturated with water and the Quaternary material was partially drained

IV area without groundwater lowering.

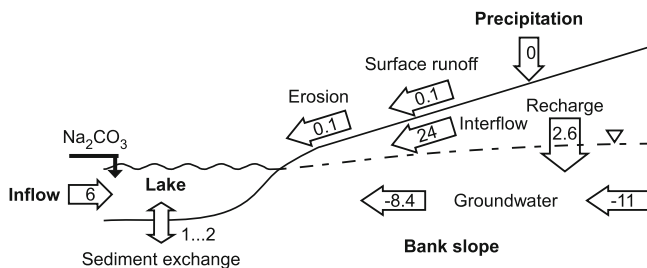
The separation of Tertiary and Quaternary strata in German lignite mines is important since the Quaternary material usually does not contain pyrite whereas it is common for the Tertiary strata. In other regions where such a separation is not necessary, the concept can easily be adapted by reducing the number of zones. Extension of the zones generally depends on the local hydrogeological conditions of a particular mine site. For the conditions of the Central German lignite mining district, Grützmacher et al. (2001) reported 1–6 m thickness for zone Ia, up to 500 m extension for zone II, and 500–2000 m extension for zone III.

As long as the water level in a pit lake is considerably lower than the groundwater level, a significant amount of the underground strata will remain aerated and may form a long term source of acidity until all of the pyrite is oxidized and the acidic products are washed out by interflow and groundwater recharge. The thickness of this aerated layer may vary over time if the groundwater level varies seasonally or inter-annually, and these variations can introduce periodic pulses of acidic inflow into the pit lake. Water level changes in the pit lake, which are typical in pit lakes that are used as reservoirs or for flood protection, will also cause groundwater level variations.

Groundwater observation wells are usually located a safe distance from the shores of pit lakes. The samples represent the quality of the groundwater, i.e. the water in the saturated part of the underground at a certain, site-specific distance from a pit lake, often located in zone III or even zone IV (Fig. 2.8). This is not necessarily the quality of the groundwater that eventually enters the pit lake because special sampling devices for the interflow and shallow groundwater observation wells very close to the shore of the pit lakes are not common. Therefore, the rate that acid is imported into pit lakes is often underestimated when it is only based on typical groundwater sampling.

An exception to this situation was reported by Heinrich et al. (2011). An investigation considering all components of potential acidity imported into Lake Bockwitz (Germany) included groundwater monitoring close to the lake shore and at the typical distance, seepage water from interflow and groundwater recharge, inflow from pit lakes located up-gradient, local precipitation, local surface runoff, erosion from the sidewalls above the water level of the lake, water quality inside the lake, interaction with the sediment of the lake and outflow from the lake. Column tests were operated to determine the rate of pyrite oxidation in the vadose zone and the elution rates in the permanently saturated zone. These results, combined with a groundwater flow model that was calibrated with actual observations, allowed for the development of a detailed balance of acidity in Lake Bockwitz. The result is depicted in Fig. 2.9. For more details, see Heinrich et al. (2011).

Interflow was a major influx of acidity into Lake Bockwitz in 2010, i.e. 5 years after reaching the final lake level (Fig. 2.9). The water level of Lake Bockwitz was about 15–20 m below the surrounding landscape, which may have caused the



**Fig. 2.9** Detailed balance of acidity for Lake Bockwitz (Germany; modified from Heinrich et al. 2011). The data give the average fluxes of acidity for 2010 in  $\text{kmol d}^{-1}$ . Negative values indicate alkalinity fluxes

interflow contribution to be exceptionally high. Nevertheless, Lake Bockwitz demonstrates the importance of interflow and the processes that take place above the water table in the vicinity of a pit lake on pit lake acidification. Therefore, this component should be considered and, as far as possible, quantified when establishing acidity-alkalinity-balances of pit lakes or designing neutralization measures.

Like the above-mentioned concept of zones of lowered groundwater, the example of Lake Bockwitz originates from Germany where mining takes place in unconsolidated rock. The basic ideas described above also apply to pit lakes in hard rock environments and intermediate conditions, such as porous rock, e.g. sandstone. Often, soil cover and the weathered zone provide conditions similar to that present in unconsolidated rock. Waste rock dumps are also similar to unconsolidated rock with respect to water flow and the interaction between the air in the underground pores and the minerals.

Of course, the relationship between groundwater and pit lakes is a two-way street; pit lakes are influenced by groundwater, but also influence groundwater. For example, evaporation from a lake surface and surficial outflows of pit lakes can cause a long term depression of the groundwater surface in the vicinity of the lakes. If there is a subsurface outflow from a pit lake, the lake is a source of water and contaminants to the down-gradient groundwater. Also, pit lakes often interconnect different aquifers, which may otherwise be separated; these pit lakes act like a mixing, aeration, and reaction chamber. The outflowing water has a different water quality than the influent groundwater. Even if groundwater of a deep aquifer only passes through the anoxic monimolimnion of a meromictic pit lake, the water quality will be changed in the lake, since the permanent input of substances into the monimolimnion by sedimentation changes the geochemistry of the water. Such aspects all have to be considered when assessing interactions between groundwater and pit lakes.

To summarize, there are often intense and important interactions between groundwater and pit lakes. Which kind of influence dominates at a particular pit lake depends on local conditions. However, this book is focused on the lakes, and so, such groundwater aspects are only addressed in [Sects. 3.2.2, 4.6, 5.3, 5.5, 5.8,](#) and [Chap. 6](#).

The interactions of groundwater and a pit lake were extensively investigated at the Berkeley pit lake. They are briefly described in case study 5.5 in this book. More details can be found in Gammons et al. (2009), Pellicori et al. (2005), and in a special issue on the topic in *Mine Water and the Environment* (Kleinmann 2006). Further case studies on the interaction of groundwater and pit lakes in Germany exist, such as: Bozau and Strauch (2002), Trettin et al. (2007), and Werner et al. (2001, 2008).