Causes of an distinct metalimnic oxygen gradient in the pit lake Senftenberger See in summer 2013 as a case study

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Abstract

The lake Senftenberger See is a pit lake in the Lusatian lignite mining area in Germany and originated between 1967 and 1972 in the former lignite open cast mine Niemtsch. In summer 2013, a distinct oxygen gradient in the metalimnion with the oxygen concentration sharply decreased to 0 mg/L and in succession a high mortality rate in a fish farm was observed. At the same time, the Koschen channel with a lock connecting the nearby pit lake Geierswalder See started operation and increased the input of ferrous iron. In June 2013, a flood of the river Schwarze Elster passed through the lake.

The investigation of the causes of the observed distinct oxygen gradient was based on a systems analysis approach. All available meteorological, hydrological, limnological, hydrochemical, and biological data were analysed. A dynamic water balance model and a stratification model for the lake Senftenberger See were assembled. The stratification model was created as a 2D-model based on the model software CE-QUAL-W2 and was calibrated on the basis of measured temperature profiles.

The thermal stratification behaviour of the lake Senftenberger See was simulated for a time series. The effect of specific water balance variables on the water quality of the lake Senftenberger See was quantified by modeling the migration of a conservative tracer. The investigation results showed that the meteorological conditions in the year 2013 caused the distinct temperature and oxygen gradient in the metalimnion. The channel between the lake Geierswalder See and the lake Senftenberger See as well as the flood in June 2013 could be excluded as a cause. The long-term monitoring shows that the distinct metalimnic oxygen gradient was not a singular event in summer 2013. Similar conditions were observed in the lake Senftenberger See in previous years and in 2013 in other pit lakes, too.

It has been shown that the 2-dimensional limnophysical modeling with CE-QUAL-W2 is well suited to simulate the thermal stratification and the spatial migration of solutes in highly structured pit lakes. The simulated stratification of the Senftenberger See was in good accordance with the measured data. The model thus represents a good base for the further examination of additional water quality problems and its application to other pit lakes.

Key words: pit lake, metalimnic oxygen gradient, limnophysical modelling, solute transport modelling

1 Basics

The lake Senftenberger See is a pit lake in the Lusatian lignite mining area in Germany (fig. 1). The lake originated between 1967 and 1972 in the former lignite open cast mine Niemtsch. The Senftenberger See is a positive example for the post mining revitalization of the landscape and multivalent usage of a pit lake. On the lake Senftenberger See nature and landscape protection areas, sport and tourism as well as low water management, flood protection and fishery exist in parallel nearly without conflicts.

At the highest water level of +99.25 m NHN the lake Senftenberger See has a surface area of nearly 12 square kilometers and a total volume of 80 million m³. Thereof, around 16 million m³ are usable for water management. The lake Senftenberger See is divided into four deep basins: West, North, East and South (fig. 2). The first three basins are connected by shallow areas. The south basin, however, is connected only by a narrow and flat channel with the rest of the lake and largely hydraulically separated. In the middle of the lake Senftenberger See is an island with a large shallow bay. At the highest water level the lake is in average 6.2 meters deep and the maximum water depth is approximately 25 meters.

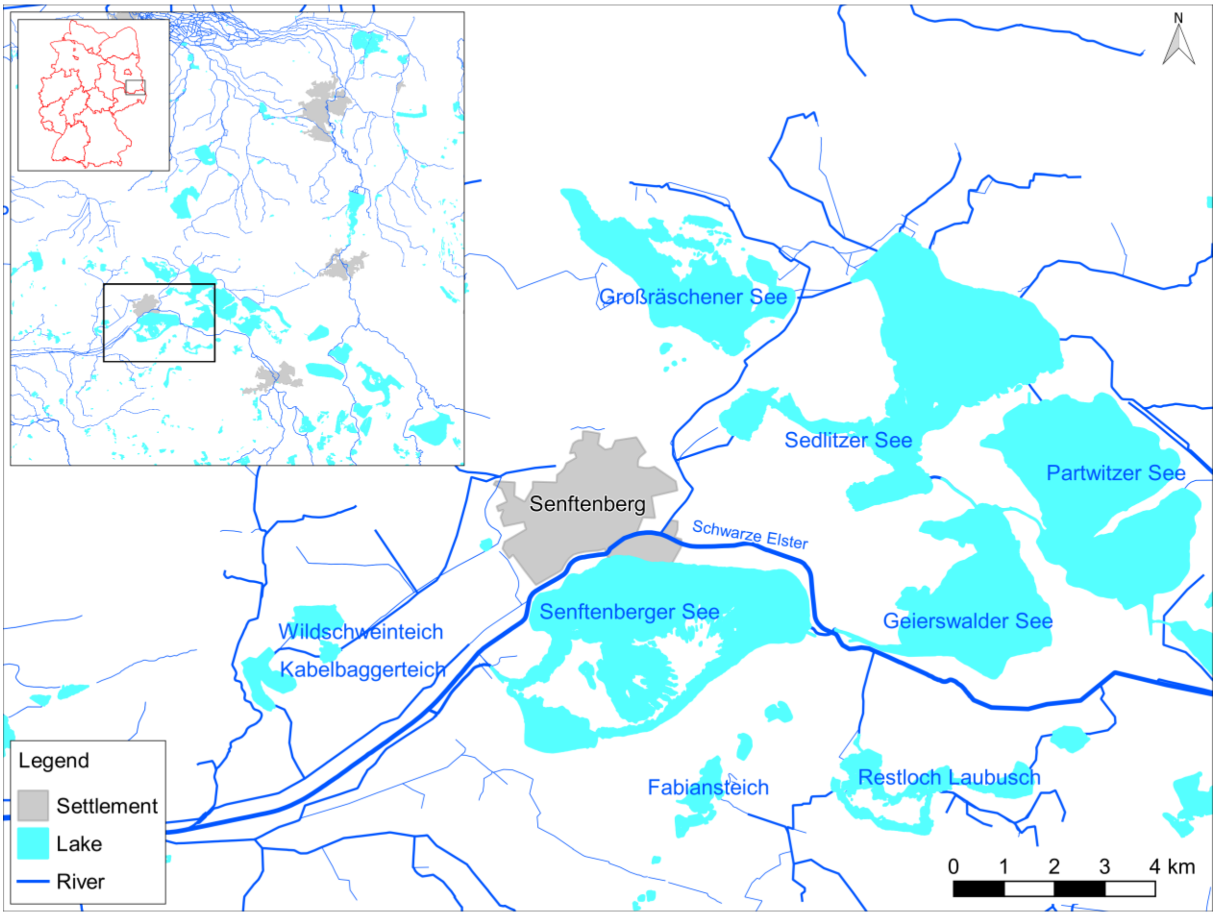

Figure 1: *Location of the lake Senftenberger See*

The lake Senftenberger See is located in the bypass of the river Schwarze Elster. The inlet from the river Schwarze Elster is located in the east and the outlet in the west (fig. 1). In July 2013, a traversable channel with a lock, the so called Koschen channel, started operation. The channel connects the nearby pit lake Geierswalder See with the lake Senftenberger See and increases the water inflow to the lake Senftenberger See.

The reservoir of the lake Senftenberger See is usually filled during the hydrological winter season (November to April) and discharged over the summer season. The water surface level of the lake Senftenberger See oscillates between +98 m NHN and +99 m NHN. The water level of +99 m NHN is only exceeded during flood events. In average of the years 1997 to 2012 approximately 0.80 m^3/s discharged into the lake Senftenberger See from the river Schwarze Elster and 0.79 m^3/s discharged back into the river Schwarze Elster. The average atmospheric water balance is with -0.02 m^3/s in deficit. Between June and November 2013 an average flux of 0.15 m^3/s discharged from the Koschen channel. Thereof a flux of approximately 0.05 m^3/s are originated from the lock operation itself and approximately 0.10 m^3/s from the lock bypass.

Since there were no data on the groundwater balance of the lake Senftenberger See, the net groundwater balance had to be determined as a residual of the sea water balance. By the year 2010, the Senftenberger See had a deficit in groundwater balance with a net loss of 0.1 m^3/s. Since then, the groundwater balance is excessive. For the year 2013 a net surplus of 0.3 m^3/s was determined. The change in the groundwater balance is a result of regional rise of the groundwater level subsequent to the restoration of former mining areas. The direct groundwater inflow to the Koschen channel is about 0.05 m^3/s. The average water balance of the lake Senftenberger See for the years 1997 to 2012 and in comparison the year 2013 is shown schematically in fig. 3.

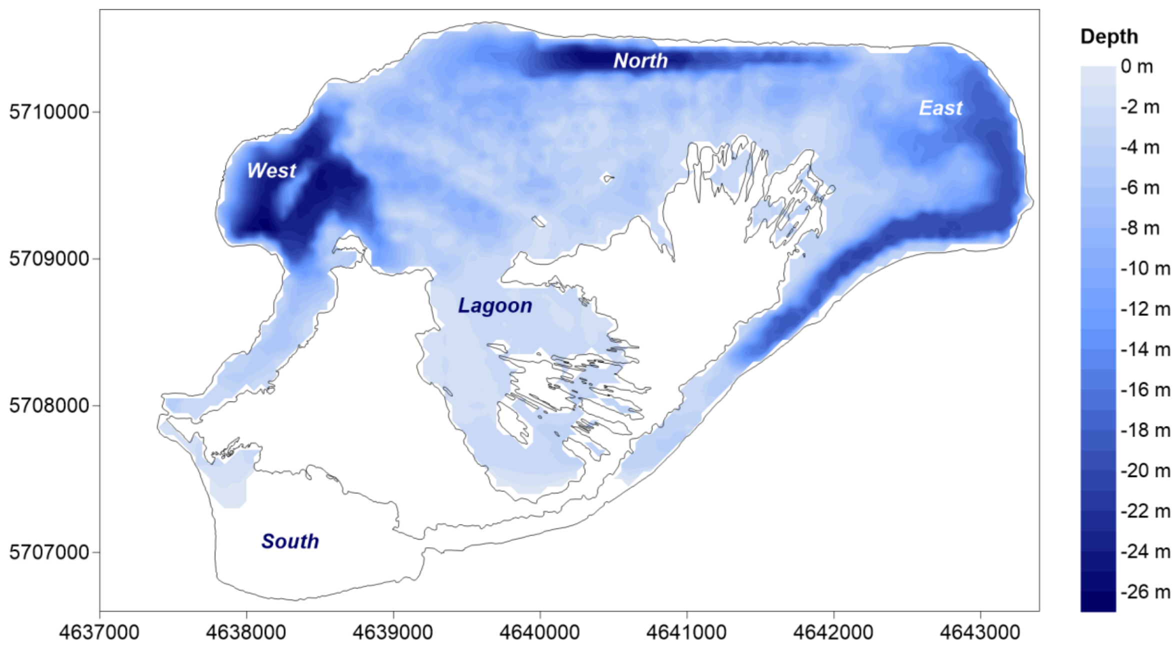

Figure 2: *Water depths in the lake Senftenberger See at a water level of +99.25 mNHN (There is no bathymetry data available for the south basin)*

In recent years, the lake Senftenberger See was only event-driven limnologically, hydrochemically and biologically investigated. In the hypolimnia of the deep basins oxygen-free conditions were recorded regularly in the summer months. Very low oxygen concentrations were also measured in the metalimnion of the lake repeatedly. This distinct oxygen gradient in the metalimnion is also observed in other pit lakes of the Lusatian area with similar limnological conditions. These lakes are characterized by a small hypolimnion volume and a significant groundwater influence.

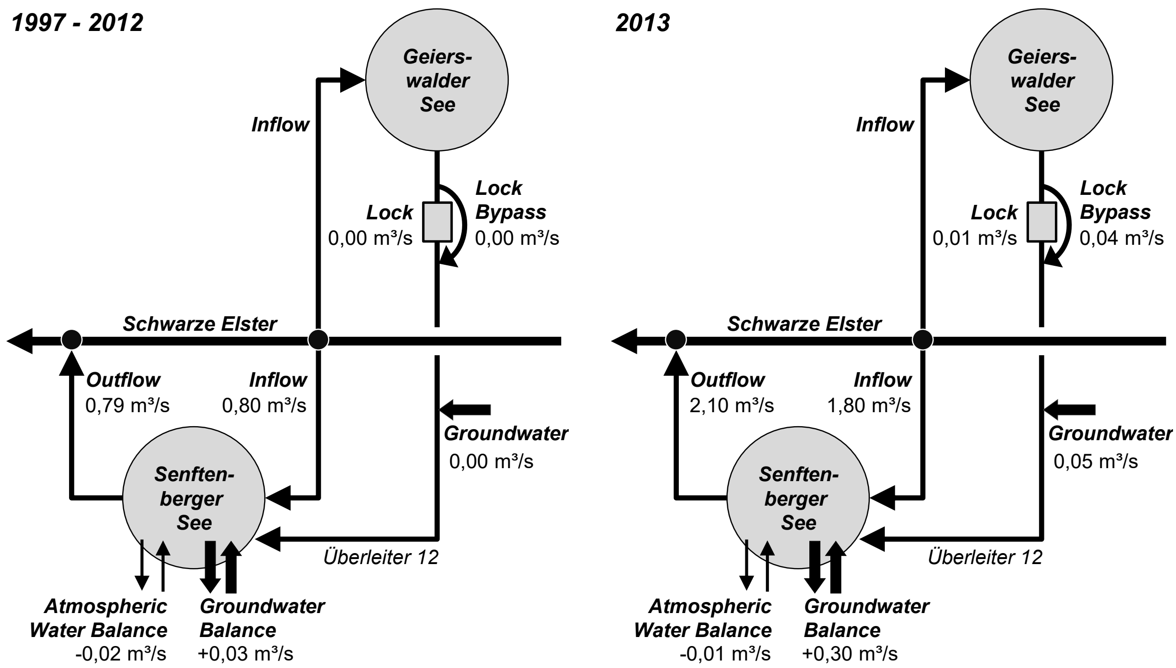

Figure 3: *Average water balance of the Senftenberger See for the years 1997 to 2012 (left) compared with the year 2013 (right)*

The groundwater that flows to the lake Senftenberger See from the surrounding former mining area has iron concentrations of 35 to 140 mg/L. The effects of iron influx are yet harmless and invisible. The water in the Koschen channel has iron concentrations between 1 and 5 mg/L. The oxidized iron settles as iron hydroxide along the channel and has a negative effect on the appearance.

2 Incidents in summer 2013

In summer 2013, a high mortality rate in a fish farm in the west basin of the lake Senftenberger See was observed. Subsequent measurements showed a distinct oxygen gradient in the metalimnion of the lake Senftenberger See, wherein the oxygen concentration sharply decreased to 0 mg/L. At the same time, the lock in the Koschen channel started operation. So the distinct metalimnic oxygen gradient and the high mortality rate in a fish farm have been associated with the increased iron input from the channel. Therefore the lock operations and the lock bypass were stopped by the authorities until the causes of the metalimnic oxygen gradient in summer 2013 are clarified.

3 Working hypothesis

For the metalimnic oxygen gradient in the lake Senftenberger See in early summer 2013 and the subsequent loss of fish, the following six events or their combination came into consideration.

1. The start of the regular lock operations in the Koschen channel.
2. The discharge of water from the Geierswalder See over the lock bypass.
3. The retention of a considerable amount of the flood in June 2013.
4. The stable thermal stratification of the lake under the influence of an unusually strong increase in air temperatures in spring.
5. The groundwater influx of ferrous iron into the Koschen channel and subsequently in the lake Senftenberger See.
6. The increasing groundwater influx of ferrous iron in the lake Senftenberger See from the surrounding former mining area.

4 Problem analyses

A systems analysis approach was used to investigate the causes for the observed distinct metalimnic oxygen gradient. All available meteorological, hydrological, limnological, hydro-chemical and biological data were collected and analysed.

The analysis of an 18-year meteorological data series showed, that the average meteorological conditions in the year 2013 were widely common. The weather of the year 2013 was characterized by a very cold March, a fast increase of air temperature in April, a stable warm weather period in the spring and six hot weeks during the summer from late June to early August.

In average of the year 2013 approximately 1.80 m³/s discharged from the river Schwarze Elster into the lake Senftenberger See and 2.1 m³/s discharged back into the river Schwarze Elster. In order to avert a flood in June 2013, about 2.9 million m³ were retained in the lake Senftenberger See within four days. From the Koschen channel on average 0.03 m³/s were discharged into the lake Senftenberger See. The net groundwater inflow was determined with 0.35 m³/s. The atmospheric water balance over the surface of the lake Senftenberger See was slightly in excess in the year 2013 (fig. 4).

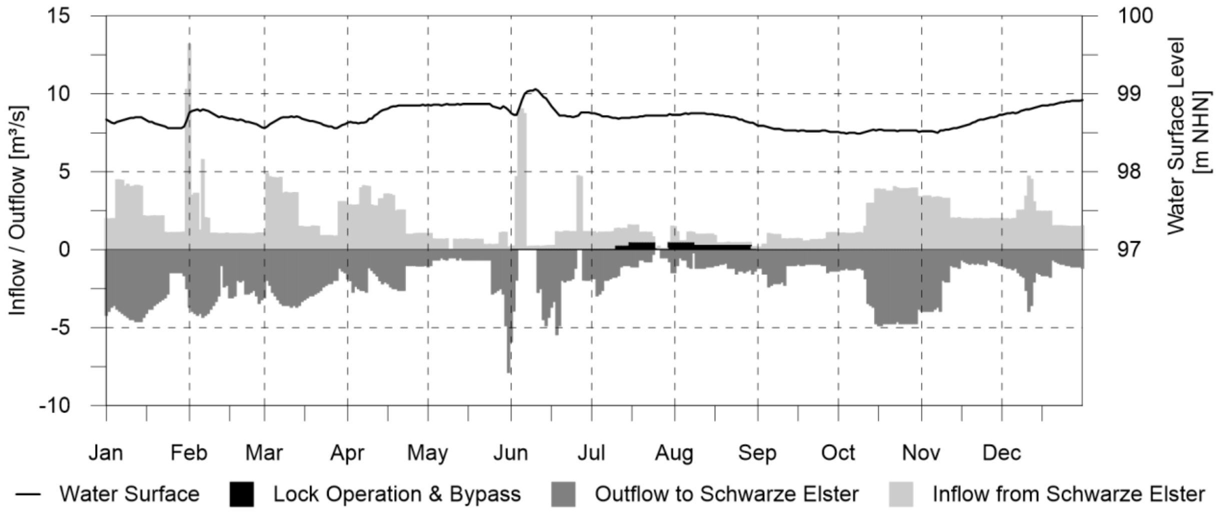

Figure 4: *Surface water balance of the Senftenberger See in the year 2013*

On average of the year 2013 only 3 % of the overall inflow to the lake Senftenberger See originates from the lock operation and the lock bypass in the Koschen channel and from the seepage of groundwater into the channel (fig. 4). If a representative iron concentration is assigned to every inflow component, an iron inflow balance can be calculated (see tab. 1). Accordingly, at least 46 % of the total iron input into the lake Senftenberger See comes from the seepage of groundwater and about 42 % from the discharge of the river Schwarze Elster. The iron input into the Koschen channel is around 157 kg/d. The vast majority of the iron already deposits as iron hydroxide along the Koschen channel, so that only a small fraction reaches the Senftenberger See. This iron is also highly oxidized and thus has a very low respiration potential.

***Table 1:** Balance of the iron influxes into the lake Senftenberger See in the year 2013*

source	mean influx	representative iron concentration	mean iron load	
	m^3/s	mg/L	kg/d	prop.
Net groundwater inflow into the Senftenberger See	> 0,300	25 [2)]	> 648	46,6 %
discharge from the Schwarze Elster	(1,800)		586 [3)]	42,1 %
groundwater inflow to the Koschen channel	0,050	36 [1)]	156	11,2 %
lock operation and bypass in the Koschen channel	0,050	0,5	1	0,1 %
Sum			> 1.391	100,0 %

[1), 2)] Averaged iron concentration of the groundwater in the specific inflow area
[3)] Mean annual iron load calculated by reference date measurements

The vertical temperature profiles for July, August and September 2013 showed a distinct temperature gradient between the epilimnion and the hypolimnion in the east, west and north basin and therefore a very stable thermal stratification of the lake Senftenberger See. The vertical profiles also showed a distinct oxygen gradient in the metalimnion, whereat in the north and west basins the oxygen saturation declined to 0 % below the thermocline (fig. 5). In contrast the pH-value, the turbidity and the electrical conductivity shows no significant vertical gradients.

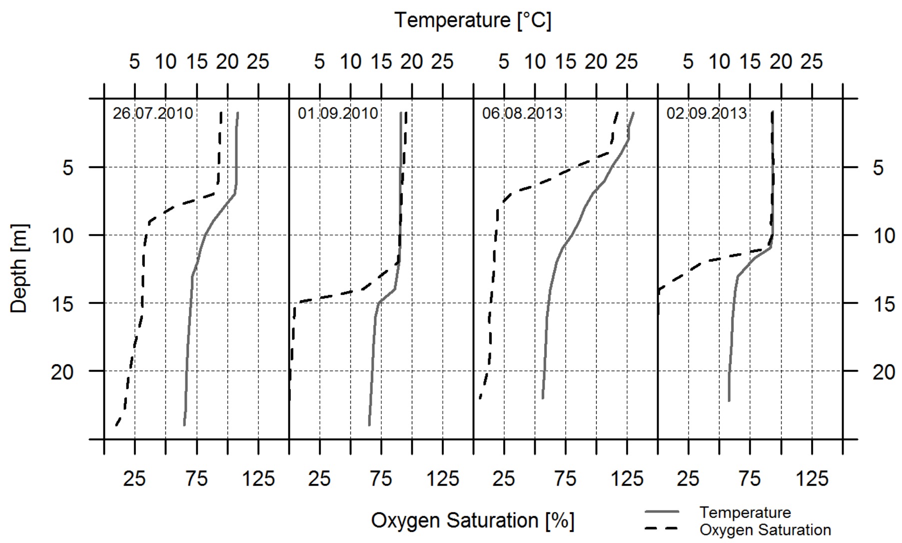

***Figure 5:** Vertical profiles of water temperature and oxygen saturation in the northern sub-basin of the Senftenberger See*

5 A model for the lake Senftenberger See

5.1 Model assembly

For a more detailed analysis of the processes in the lake Senftenberger See and their interaction a two-dimensional thermal stratification model was assembled with the software CE-QUAL-W2. With this approach, the highly structured bathymetry of the lake Senftenberger See could be adequately taken into account. The developed stratification model consists of 15 longitudinal segments. The vertical discretization between the levels +99.5 and +97.5 m NHN was carried out in 0.1 meter intervals and below +97.5 m NHN in 0.5 meter increments. At a maximum water level of +99.0 m NHN and a maximum depth of +74 m NHN, the model has 62 vertical layers.

5.2 Model calibration

The stratification model was calibrated on the basis of measured temperature profiles (fig. 6). With the calibrated model the thermal stratification of the lake Senftenberger See was simulated for an 18-year time series (years 1997 to 2014) of meteorological and hydrological data. The model results showed, that the three relevant basins east, north and west have different vertical temperature gradients and circulation characteristics, although they are connected in the epilimnia. Because of the extended wind exposure of the east-west aligned north basin, the epilimnion and in particular the metalimnion are more spacious as in the east and west basin. The autumnal circulation reaches the ground in the north basin on average one month earlier than in the basin east. The full circulation in the basin west is delayed by one more month.

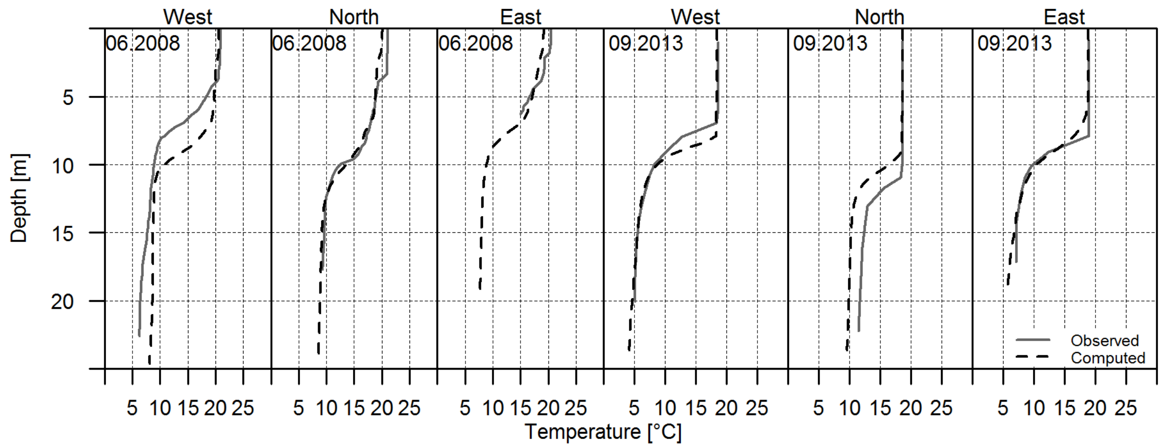

Figure 6: *Comparison of the observed and modelled temperature profiles in the Senftenberger See*

5.3 Model application

Model simulations using a non-reactive migration approach were run to understand the effects of selected boundary conditions (groundwater, flood from the river Schwarze Elster and the discharge from the Koschen channel) on the temporal and spatial changes of the water quality in the lake Senftenberger See. For that, each boundary condition was assigned a fictitious non-reactive solute concentration of 100. The water temperature of the selected inflow was set according to its natural conditions. The stratification of the boundary condition inflow depends on the water temperature.

5.4 Model results

By using a fictitious non-reactive solute concentration for the boundary condition inflow, the spatial and temporal spread of this inflow in the lake Senftenberger See under the hydrological, meteorological and limnological conditions in summer 2013 could be reproduced.

The inflow from the flood in June 2013 briefly reaches a maximal volume share of 15 % in the sub-basin east (fig. 7). Within 10 days the flood inflow reaches the sub-basin west with a maximum volume share of 8 %. The flood inflow in June 2013 had only a temporary effect on the lake Senftenberger See. On complete lake overturn in autumn, the volume fraction of the flood in the entire lake declined to less than 3 %. The nutrient influx of the flood is unknown. Due to the timing of the events and the high dilution in the lake the nutrient influx of the flood in June 2013 comes not in consideration as the cause of the metalimnic oxygen gradient that occurred in the early summer.

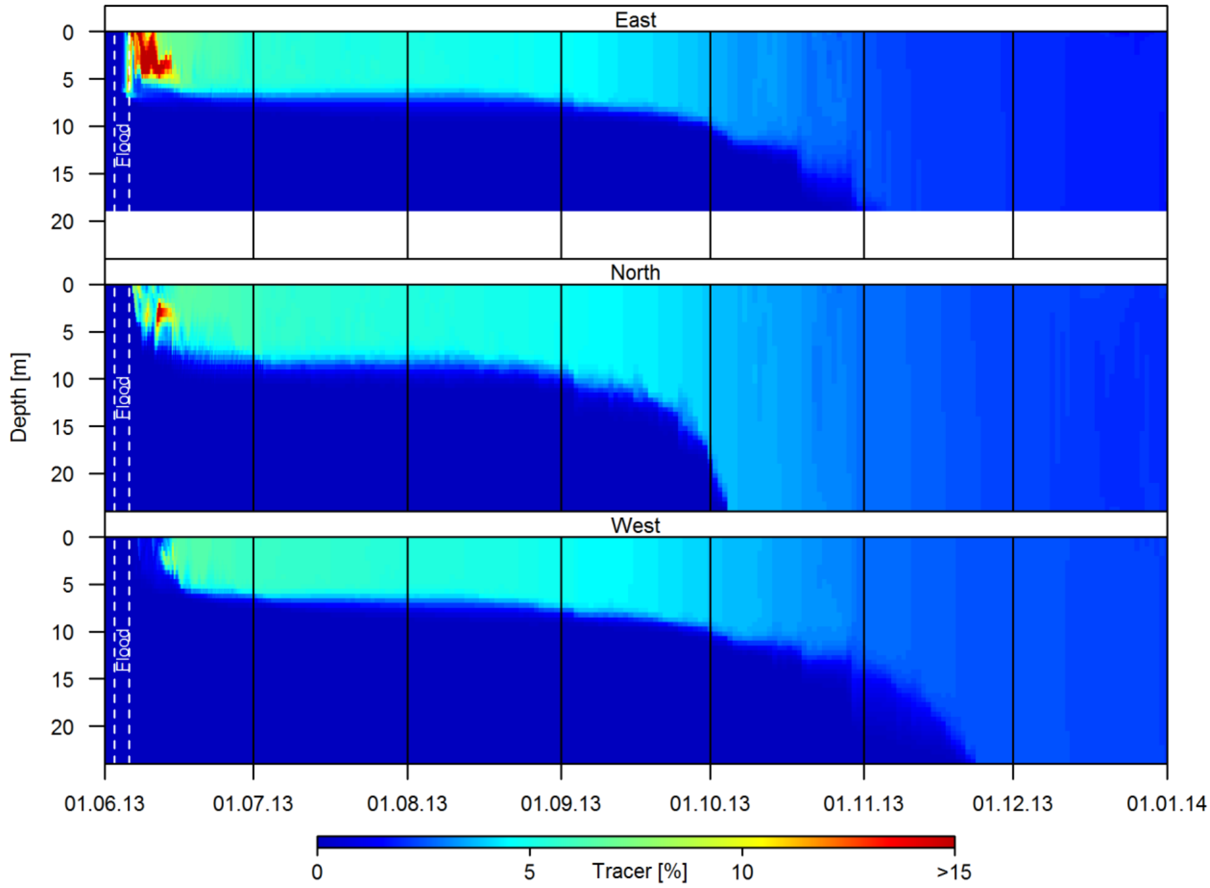

Figure 7: *The impact of the flood in June 2013 on the lake Senftenberger See illustrated by the spread of a non-reactive tracer (the color scale shows the proportion of river water in the three main basin of the lake Senftenberger See)*

The seepage of groundwater into the lake Senftenberger See comes from the surrounding former mining area and therefore is rich in ferrous iron. The groundwater exfiltrates due to the geohydraulic conditions mainly into the east sub-basin of the lake Senftenberger See. It mixes due to water temperature preferably in the metalimnion and could gain there a volume share of more than 25 %. In the hypolimnion the groundwater has an average volume share of 15 %. Due the distinct vertical temperature gradients in summer 2013 and the thereby inhibited vertical water exchange, the groundwater accumulated in the hypolimnion of all sub-basins to volume fractions of 20 % to 25 %. The iron concentration in the groundwater ranges from 35 to 140 mg/L. To fully oxidize this iron, between 5 to 20 mg/L oxygen is required. The accounting shows that the groundwater influx has a large fraction on the overall oxygen consumption potential in the lake Senftenberger See and is a possible cause of the metalimnic oxygen gradient.

For a short period of time the iron contaminated discharge from the Koschen channel gained a maximal volume share of 7 % in the sub-basin east. The discharge reaches the sub-basin west with a one month delay and gained there a maximum volume share of 4 % in September 2013. This effect is occurred three months after the high mortality rate in the fish farm and therefore could not be the cause of the distinct metalimnic oxygen gradient. The groundwater infiltrating in the channel of the Koschen channel has a ferrous iron concentration of less than 35 mg/L and therewith an oxygen consumption potential of 5 mg/L. At a maximum volume fraction of 3 % the potential oxygen consumption caused by the groundwater inflow is less than 0,15 mg/L. From a hydrochemical point of view, this low consumption potential could not be the cause of the metalimnic oxygen gradient. Furthermore the discharge from the Koschen channel mixes due to water temperature in the epilimnion of the sub-basins east and north and is oxidized there safely.

6 Interpretation

The analysis of the available long-term data showed, that a high oxygen consumption in the hypolimnion of mining pit lakes could cause a subsequent oxygen gradient in the metaliminion. Normally the oxygen concentration in the pit lakes does not drop below 4 mg/L (oxygen threshold value for fish). However, in summer 2013 the oxygen concentration undercut this limit in combination with the typical oxygen gradient in the metalimnion. For the first time, a water user was directly affected by such an event.

The measurement of the lakes stratification first started after the notification of the high mortality rate in the fish farm, so the event is not well documented. The actual public perception is dominated by the large-scale clogging of river waterbodies by iron hydroxide sediments as a result of the regional groundwater level rise after the closure of the nearby lignite mines. Therefore, a causal connection between the high mortality rate in the fish farm in the sub-basin west and the discharge from the Koschen channel into the sub-basin east was assumed.

Even if the oxygen consumption in the meta- and hypolimnion of the lake Senftenberger See is only caused by the oxidation of the iron input, the operation and bypass of the lock in the Koschen channel could be safely ruled out as a cause of the distinct metalimnic oxygen gradient in summer 2013. The discharge from the Koschen channel has an average share of 3 % of the total inflow. In addition, the groundwater exfiltration into the Koschen channel accounts for only around 11 % of the total iron input into the lake Senftenberger See. Furthermore, most of the inputted iron oxidizes and settles as iron hydroxide along the channel, so that only a small fraction of the inputted iron reaches the sub-basin east of the lake Senftenberger See at all. Compared to that, the iron input with the discharge from the river Schwarze Elster and the groundwater is three to four times as high (see tab. 1).

The modelling of the thermal stratification also showed that the discharge from the Koschen channel as well as the discharge from the river Schwarze Elster only mixes in the epilimnion of the sub-basin east, where a sufficient amount of oxygen is available for the iron oxidation. In contrast the groundwater due the water temperature preferably mixes in the metalimion of the sub-basins and has thus a significant share at the metalimnic oxygen consumption in the Senftenberger See.

A special weather-related characteristic of the year 2013 is the rapid warming of the lake Senftenberger See and the fast emergence of the epilimnion in the spring in succession of an extreme air temperature rise in combination with poor wind conditions. These conditions led to an exceptionally distinct temperature, oxygen and density gradient between the epilimnion and the hypolimnion.

The extraordinarily density difference between the epilimnion and the hypolimnion led to an accumulation of easily degradable products of primary production and a high intensity of heterotrophic processes in the metalimnion. This caused an extremely distinct gradient of oxygen concentration in the metalimnion. Furthermore, this effect benefited from the adverse limnological conditions in the lake Senftenberger See:

- the special bathymetry of the lake Senftenberger See with an adverse proportion of the epilimnia and hypolimnia volumes
- the increased discharge from the river Schwarze Elster and
- the associated increased nutrient input.

The evidence obtained point to a combination of several causes for the formation of the distinct metalimnic oxygen gradient in early summer 2013. The decisive factors were mainly the increasing ferrous iron input with the groundwater and the special meteorological conditions in 2013. The discharge from the Koschen channel could be definitely ruled out as the cause of the metalimnic oxygen gradient due the low iron load and the mixing into the epilimnion.

Acknowledgements

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