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Impact of regional groundwater flow on the water quality of an old post-mining lake

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Abstract

Investigations have been carried out on a post-mining lake (Lake Senftenberg) near the town of Senftenberg, Germany, which was flooded 25 years ago. In its close vicinity several mines have just been abandoned or will be abandoned in the next few years. A change of the local hydrologic flow system is expected. All water levels in post-mining lakes in this area will be controlled to maintain a level low enough to prevent buildings from being damaged. The lakes and most surface waters in this area are influenced by acidic mine drainage. Based on a regional groundwater model, geochemical mass balance calculations were performed. Water quality changes due to the oxidation, hydrolysis and precipitation of metals were investigated. These calculations reveal a high probability of acidification for the investigated Lake Senftenberg. The surrounding post-mining lakes will reach a higher water level than Lake Senftenberg. Thus, after 2010, ground water from the north will flow through large overburden dumps and infiltrate Lake Senftenberg.

Keywords: Geochemical mass balance calculations; Regional groundwater flow; Water quality; Reaction modeling; Post-mining lakes

1. Introduction

Extensive open-cast lignite mining has created a vast water deficit in the Niederlausitz mining area of Germany. The groundwater cone of depression in this area has created a groundwater deficit of approximately 9 billion m^3. The lakes that will be established in flooded open-cast mines will have a total water volume in the Niederlausitz area of approximately 4 billion m^3. To manage the water resources during the replenishment of the water deficit, predictive tools are needed to evaluate the planned measures. The objective of our work was to develop and demonstrate such a tool to evaluate the feasibility of remediation goals with respect to the water quality of a post-mining lake. We aim to predict hydrogeological conditions that are formed by the regional flow system. Based on these conditions we evaluate the effects of aeration, oxidation and precipitation on the water quality. Furthermore, the effects of seepage waters from unsaturated dump areas and from the erosion of dump slopes are evaluated. Key questions that had to be addressed concerned the

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future use of Lake Senftenberg as a recreational area and whether the water quality of the discharge of the lake may in the future exceed maximum allowed concentrations.

1.1. Description of the investigated site

The Niederlausitz Mining District is located east of the Elbe River Valley, in Germany, about 150 km southeast of the capital, Berlin. Lake Senftenberg (Senftenberger See), which is located in the core region of the mining district, was chosen as a test site. Its location with respect to other decommisioned mine sites is shown in Fig. 1. It was an operating mine from 1938 to 1966. Its flooding with surface water started immediately afterwards and continued until the early 70s.

The privatisation of the lignite mines in 1990 was accompanied by the decommissioning of some 40–50 mines which remained public property. Few mines where kept in operation, the Welzow-Süd mine in the upper right corner of Fig. 1 being one of them. The Lakes Sedlitz, Skado, Bluno and Spreetal in the northeast of Lake Senftenberg will be flooded in the next few years. Their water volume will be 300–600 million m^3 each.

Lake Senftenberg is subdivided by an island into two major parts, with an overall water volume of about 75 million m^3. The island consists of overburden dump material of the former mine. An elevation map of the lake bottom is shown in Fig. 2. Lake Senftenberg was flooded with water from the Schwarze Elster River over a period of about 4 years, as shown in Fig. 3. Its water level is regulated because it is used as a storage reservoir to prevent floods in the Schwarze Elster River. The lake parts north and south of the island show distinctive differences in water quality. The pH in the southern lake remained at a level of 3.5 from the time of flooding until now. The increase from pH 3 to 7 in the northern lake was achieved after the inflow point of river water was relocated to assure an effective mixing of river water and lake water. The alkalinity of the river water is 1–1.3 mmol l^{-1}, the alkalinity of the lake water is 0.3–0.5 mmol l^{-1} in the northern lake and the acidity in the southern lake is around 0.5 mmol l^{-1}. The decrease in pH in the northern lake in 1994/95 (Fig. 3) corresponds to a shutoff of the river water inflow and a maintenance of the lake water level at its regular low water level for an unusually long time (6–8 months).

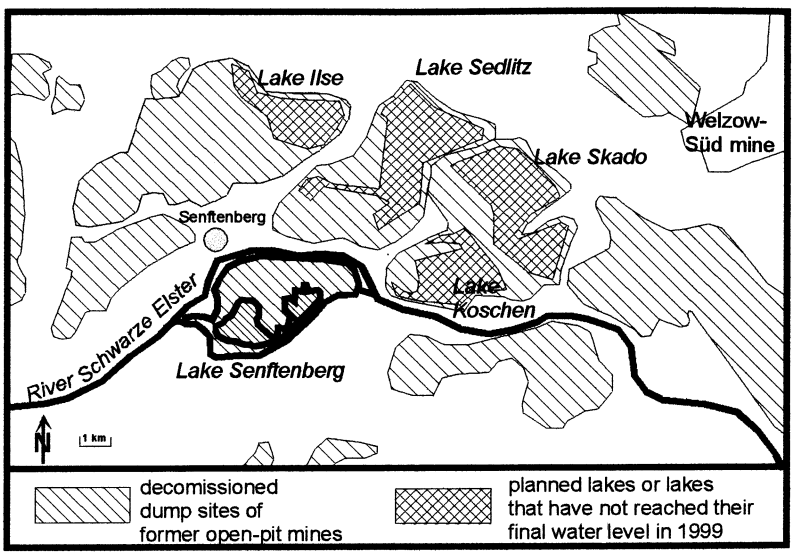

Fig. 1. Regional map showing the investigated site and surrounding former mine sites in Niederlausitz Mining District, eastern Germany.

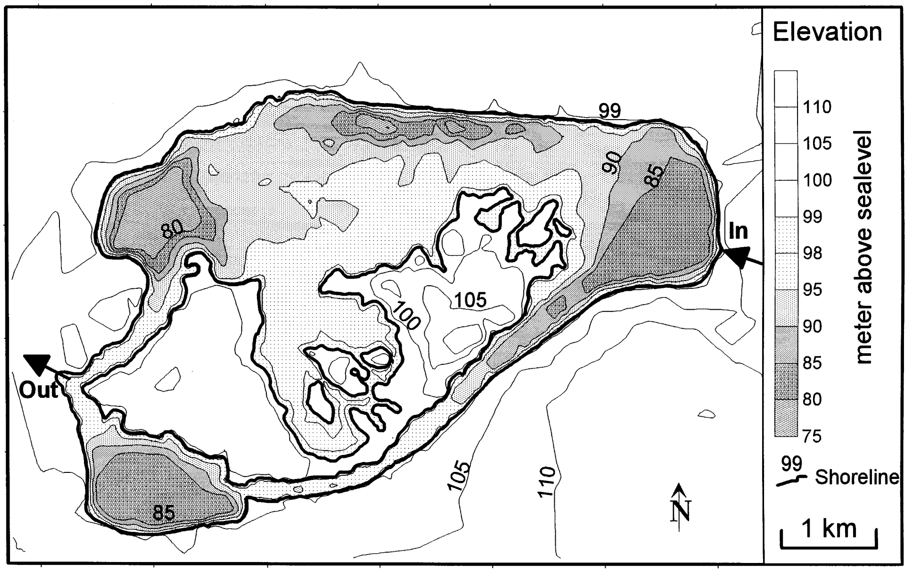

Fig. 2. Elevation map of the lake bottom of Lake Senftenberg. Parts of the overburden dump of this former mine form an island dividing the lake into a northern and a southern part.

The reason for the differing lake water qualities between the northern and southern lake is the narrow channels which connect the two parts (see Fig. 2). The main stream of river water is not flushing the southern lake effectively. The volume of northern lake is about 62 million m^3, while the volume of the southern lake is about 13 million m^3. The annual inflow of river water is about 24 million m^3. The channels connecting the lakes are only 1–2 m deep. The maximum depth of the lake basins is about 25 m. The eastern parts of the island are elevated about 2–10 m above the lake water level. Parts of the conveyor bridge dump that form the island have been covered with dump material to create a flat surface. Here the top layer was treated with fly ash and planted with pine and oak.

2. Modeling approach

Water samples were taken to analyze the concentration of various surface and groundwater fluxes around the lake. Laboratory experiments were performed to evaluate effects of pyrite oxidation and erosion. The results were used to determine the time-dependent mass fluxes into the lake and the resulting lake water quality by a combination of computer models.

2.1. Hydrogeochemical processes

2.1.1. Pyrite oxidation

Pyrite oxidation within the flooded dump is believed to have a minor effect on the water quality of Lake Senftenberg. In the unsaturated zone, no sulfides were found (Fig. 4). Sulfides that were found in the saturated zone are limited in their oxidation rates by the transport of dissolved oxygen with ground water recharge. Water level fluctuations by approximately 1 m occur in the lake due to the seasonal reservoir management. These periodical fluctuations can be interrupted for maintenance purposes as happened once in the last decade. The water level was then kept at its lower limit for about 6–8 months. This causes a drainage of parts of the dump that stay saturated during the regular management regime. Oxidation experiments on sediment samples from the saturated part of the dump with atmospheric gas in moisture chambers were carried out to simulate reactions in these drained parts. The total acidity

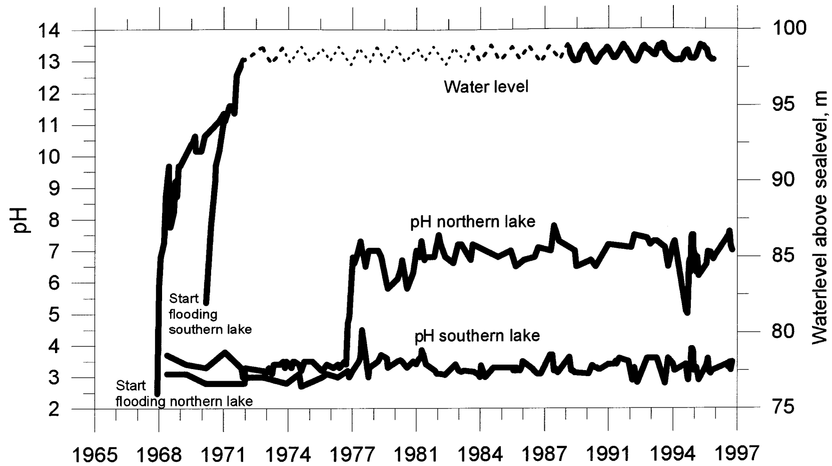

Fig. 3. Water levels and pH in the northern and the southern part of Lake Senftenberg, 1968–1997.

flux during a 6 month period of low water levels was estimated to be 39 000 mol_c per year.

2.1.2. Leaching of dump sediments by erosion

Erosion of the island is driven by surface runoff and waves. The mass flux that is driven by surface runoff was estimated to be 10 kg m^{-2} per year on the slopes along the shoreline. Investigations of the shore profiles of post-mining lakes by Wagner (1996) have shown that the erosion by waves can be estimated using a semi-empirical approach for the calculation of an equilibrium shore profile. The shape of the profile depends on the soil parameters and the site-specific exposition to wave stress. According to this theory, the slopes of the banks of the island appear to be in a steady state with respect to the mean water level. During times of low water levels, a new steady state profile starts to develop. Depending on the wave exposure, the shore inclination and the soil parameters, a sediment mass flux can be calculated. The effects of sediment elution in the lake water were investigated by titrations of lake water-sediment mixtures with lake water. Changes in the concentrations of the components Fe(II), Fe(III), Al(III) and S(VI) were analyzed. The acidity flux driven by storms was estimated to be 25 000 mol_c per year, independent of the water level. Acidity flux driven by waves was neglected for the regular water level fluctuation regime. During a 6 month period of low water levels it was estimated to be 43 000 mol_c per year.

2.1.3. Metal oxidation and precipitation in the lake

The northern lake is dimictic. This is documented by longtime monitoring of the local authorities (LUA, 1999). Characteristic oxygen profiles during summer stagnation are shown in Fig. 5. Oxygen is not depleted in the hypolimnion.

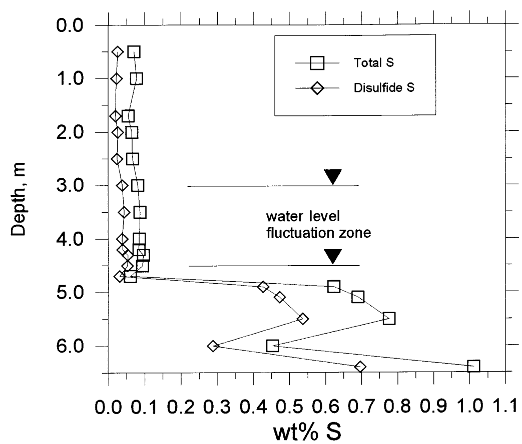

Fig. 4. Disulfide and total sulfur contents in the overburden dump that remained as an island within the lake. Each data point is representative for a 10 cm interval in depth.

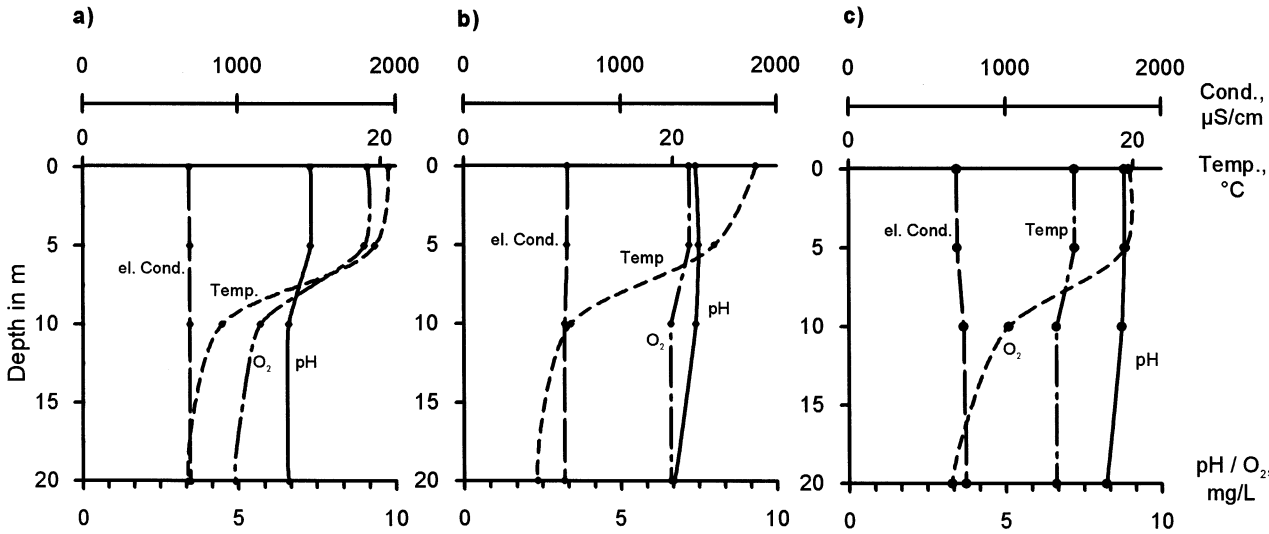

Fig. 5. Lake water stratification and oxygen content during summer stagnation for three dates: (a) 18 August 1993; (b) 1 August 1994; (c) 6 July 1995. The characteristic profiles show a temperature stratification and a decreased, but not depleted oxygen concentration in the hypolimnion. Conductivity and pH remain almost unchanged with depth.

The lake is simplified by vertical integration as a zero-dimensionsal oxic reactor. The geochemical reactions in the reactor model were defined by partial pressures of O_2 and CO_2 and the possibility to precipitate Ferrihydrite. Thermodynamic constants for Ferrihydrite were used as present in the standard database of MINTEQA2, vers. 3.11. Effective partial pressures for O_2 and CO_2 were identified from the dissolved concentration measurements to be 190 and 0.026 hPa, respectively. These values reflect a steady state that is slightly off equilibrium with the atmosphere due to the influx of carbon-rich and oxygen-depleted groundwater.

2.1.4. Mass fluxes carried by surface and ground water

The mean alkalinity flux carried by the Schwarze Elster River is about 25 million mol_c per year. The acidity flux carried by ground water is about 20 million mol_c per year for the present flow conditions. A longtime maintenance of the water level on its low level increases this flux to 26 mol_c per year. The predicted acidity flux for the flow conditions after approximately 2010 is about 70 mol_c per year.

2.2. Numerical models

As a first step, a regional 3-D groundwater flow model (using the code PCGEOFIM, Both et al., 1990) was constructed to calculate the time-dependent amount of water flux into the lake. The hydraulic fluxes change in time as the regional flow system is affected by the flooding of the mines to the north of Lake Senftenberg. The bottom of the lake was separated into discrete balance segments (as shown in Fig. 6) to distinguish between water fluxes of different origin and different ion concentration.

Mass fluxes are carried by: (i) groundwater; (ii) surface water; and (iii) erosion. For 13 different ions (components) concentrations were assigned to each of the hydraulic fluxes by sampling the groundwater in the recharge area. The overall mass flux into the lake was calculated by multiplying the ion concentrations (Table 1) which have been assigned to each flux with the water fluxes assigned to each lake segment in a geochemical balance program named RMIX (Werner, 1999). The program calculated the water quality of the lake according to the governing geochemical reactions between the solid, the liquid and the gas phase. Constant concentrations were assumed for the groundwater flux from the south and for the river water inflow. The sediment volume that may be drained during times of low water levels was calculated using the unsaturated flow code HYDRUS 2D (Simunek et al., 1999).

Erosive mass flux included transport into the lake by surface runoff and fluxes driven by wave erosion. It is affecting the mass balance calculated with RMIX but no hydraulic flux is assigned to it. The amount of mass per time that is eroded was estimated on the basis of investigations of erosion on slopes at different locations in the mining district. The leaching of soluble components from a mass of eroded sediments and the soil acidity was measured on samples in the laboratory.

A sensitivity analysis was performed concerning the variation of selected boundary conditions. The scenario for pyrite oxidation was as follows: The lake water level is kept on the low level 6 months longer than usual. Depending on groundwater velocity some of the oxidation products which are produced in the drained zone of the island are transferred into the lake during this time. The rate of pyrite oxidation in the island sediments after exposition to the atmosphere was measured using moisture cells for a period of 100 days and extrapolated at a constant rate on the 180 days of the oxidation scenario. The quality of the groundwater in the north is affected by the direction of the hydraulic gradient (see Fig. 7 for the change in flow direction). It was modeled using different scenarios for the water quality.

Balancing the mass fluxes is accomplished by a simple summation of all chemical components in all spatially separated fluxes. In combination with the water volume of Lake Senftenberg that is calculated from all in- and out-flowing water fluxes and the evaporation, a resulting water quality for the lake was calculated. The component concentrations are then passed to a reaction model. We used the equilibrium speciation code MINTEQA2 (Allison et al., 1991) to calculate the pH changes in the mixing water, and the amount

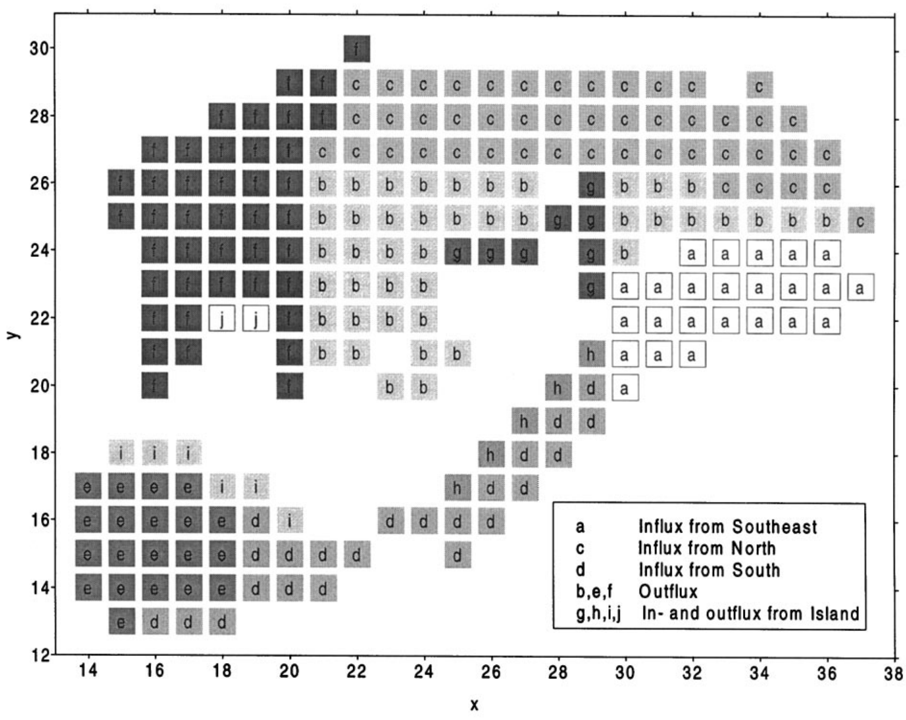

Fig. 6. Balance segments for the calculation of mass fluxes affecting the northern and the southern lake. The water flux passing through balance regions a, c and d is shown in Fig. 7. Its water quality is given in Table 1.

Table 1
Water quality parameters given as total concentrations of components[a]

Parameter	Unit	Lake Senftenberg	River Schwarze Elster	Ground-water a	Ground-water c	Ground-water d	Seepage water island
Ca^{++}	mol l^{-1}	1.5×10^{-3}	2.6×10^{-3}	3.0×10^{-3}	1.2×10^{-2}	9.5×10^{-4}	7.4×10^{-4}
Mg^{++}		5.8×10^{-4}	6.5×10^{-4}	8.9×10^{-4}	2.2×10^{-3}	4.9×10^{-4}	1.7×10^{-4}
Na^{+}		1.1×10^{-3}	1.1×10^{-3}	3.4×10^{-3}	9.0×10^{-4}	4.5×10^{-4}	5.0×10^{-4}
K^{+}		1.8×10^{-4}	2.1×10^{-4}	4.8×10^{-4}	2.5×10^{-4}	6.0×10^{-5}	3.4×10^{-4}
Cl^{+}		1.7×10^{-3}	1.1×10^{-3}	1.4×10^{-3}	8.5×10^{-4}	2.0×10^{-4}	3.6×10^{-4}
CO_3^{-}		7.2×10^{-4}	1.1×10^{-3}	2.0×10^{-4}	5.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
SO_4^{-}		2.2×10^{-3}	3.9×10^{-3}	9.0×10^{-3}	1.8×10^{-2}	4.0×10^{-3}	1.5×10^{-3}
Mn^{++}		1.0×10^{-6}	1.0×10^{-7}	2.0×10^{-5}	4.0×10^{-5}	1.0×10^{-5}	1.0×10^{-5}
Fe^{++}		1.0×10^{-7}	1.0×10^{-7}	4.0×10^{-3}	3.0×10^{-3}	1.6×10^{-3}	6.0×10^{-5}
Fe^{+++}		1.0×10^{-7}	1.0×10^{-7}	7.0×10^{-5}	3.7×10^{-4}	3.0×10^{-3}	1.0×10^{-6}
SiO_4^{-}		1.0×10^{-7}	1.4×10^{-4}	5.7×10^{-4}	1.0×10^{-3}	1.5×10^{-7}	1.5×10^{-6}
Al^{+++}		1.0×10^{-5}	1.0×10^{-6}	7.0×10^{-5}	6.7×10^{-4}	1.1×10^{-4}	1.1×10^{-4}
H^{+}		8.4×10^{-4}	1.2×10^{-3}	3.8×10^{-3}	7.7×10^{-3}	1.8×10^{-3}	2.1×10^{-3}
Alkalinity		5.0×10^{-4}	1.2×10^{-3}	-1.3×10^{-2}	-8.0×10^{-3}	-5.7×10^{-3}	-8.0×10^{-4}
pH	–	7.0	7.0	4.8	5.5	5.2	4.0

[a] Except pH and alkalinity these parameters are input concentrations for the reaction model (MINTEQA2). Parameter H (Proton Condition) is determined in an initial run prior to the input in RMIX. Groundwater a, c and d refers to the groundwater that passes through the balance segments named identically (see Figs. 6 and 7).

of solid mass that is retained in the lake due to precipitation. This algorithm is shown for one time step in Fig. 8.

3. Results

The results of the numerical models are presented in Fig. 9 and Fig. 10. The flow model clearly shows the reversal of the groundwater flow direction after the flooding of the mines in the north (Fig. 9). Their water level has to be kept at least 1 m higher than the level in Lake Senftenberg, because of the higher ground elevation in that area and the need for a free discharge into the downstream river. For the time period from 2008 on, three scenarios are modeled, each having different acidity in the groundwater flowing into the northern lake from the northern area. The different scenarios are based on an acidity of 8 (being the base case) 4, 2 and 16 mmol l^{-1} (Fig. 10). Acidity is transported into the lake mainly by ferrous iron. Oxidizing conditions in the lake lead to an oxidation of iron and a precipitation of ferric iron. Each mole of ferrous iron can potentially create an acidity of 2 mol, if the described constraints are put on the rock/water/gas system. Exact values depend on the speciation of the components. Protons that are released in the course of the reactions cause a declining pH in the lake. Predicted sulfate concentrations in the lake rise up to about 600 mg l^{-1}, the pH value in the zero-dimensional model drops below pH 6. As the lake water alkalinity declines, the lake becomes less stable to resist pH changes. The probability for significant drops in the lake water pH, as occurred in 1995 (see Fig. 3), will increase.

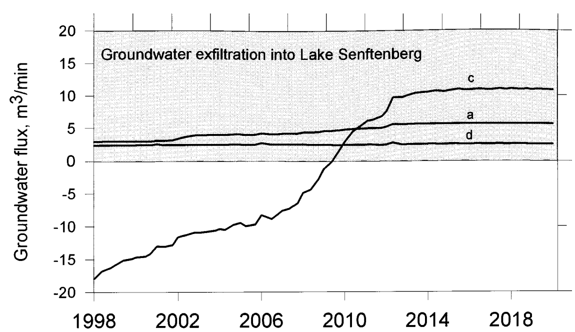

Fig. 7. Predicted groundwater fluxes into the northern lake. Negative values indicate a loss with respect to groundwater. The fluxes are a sum over all the elements shown in Fig. 6 that are labeled identically.

$$\sum_{j=1}^{j}\int_t^{t+\Delta t}\dot n_i^{Z,j}dt \pm \sum_{l=1}^{L}\left(\pm\int_t^{t+\Delta t}\dot n_i^{RS,ho,l}dt\right)+\sum_{m=1}^{M}\left(\pm\int_t^{t+\Delta t}\dot n_i^{RS,he,m}dt\right)-\sum_{k=1}^{K}\int_t^{t+\Delta t}\dot n_i^{A,k}dt = n_{i,t+\Delta t}^{RS}-n_{i,t}^{RS}$$

$$\sum_{j=1}^{j}\int_t^{t+\Delta t}\dot V^{Z,j}dt - \sum_{k=1}^{K}\int_t^{t+\Delta t}\dot V^{A,k}dt = V_{t+\Delta t}^{RS}-V_t^{RS}$$

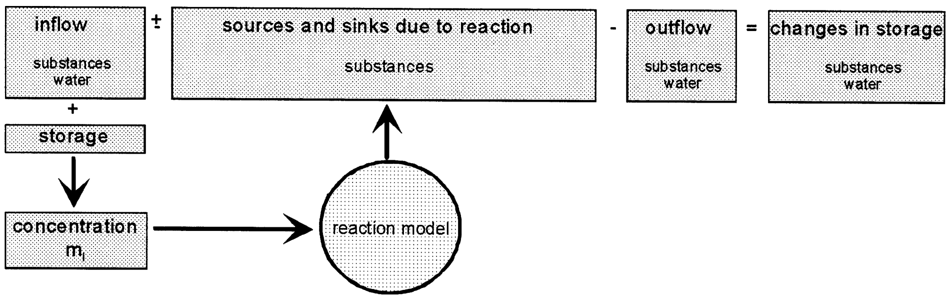

Fig. 8. Mass balance algorithm to calculate water quality changes in a lake fragment due to inflow, outflow as well as sinks and sources caused by reactions, with: $\dot n_j^{Z,j}$, mass flux of constituent i in the inflow j; $\dot n_i^{A,k}$, mass flux of constituent i in the outflow k; $\dot V^{Z,j}$, water flux in the inflow j; $\dot V^{A,k}$, water flux in the outflow k; $\dot n_i^{\mathrm{RS,ho},l}$, mass flux of constituent i due to a source/sink caused by homogeneous reactions l; $\dot n_i^{\mathrm{RS,he},m}$, mass flux of constituent i due to a source/sink caused by heterogeneous reactions m.

Limits for post-mining lakes set by the Brandenburg environmental authorities are 800 mg sulfate per liter. European bathing regulations require pH higher or equal to 6. The calculated water quality almost reaches these limits. As a consequence of these results, the planning of a remedial action was recommended.

4. Discussion

Deterministic models were used to predict the effects of a water resources management strategy. The use of these models in a decision-making procedure demanded large dimensions for the model area. The groundwater flow model is three-dimensional whereas the lake model and the reaction model were simplified to zero-dimensional systems. Processes in the aquifers (partly consisting of overburden dumps) and biological primary production in the lake were not modeled. Groundwater quality exfiltrating into the lake was treated as boundary conditions. The model parameters were varied to analyze different scenarios. A selection of scenarios was presented in this paper. The magnitude of the in-lake alkalinity production due to primary production is believed to be negligible compared to the magnitude of acidity input. A scenario that takes this alkalinity source into account gave this indication. Alkalinity input from primary production can only be effective to the mass balance in the extent that organic material is deposited in the lake sediments. Estimated parameters for the mentioned scenario were: primary production of 150 g C_{org} m^{-2} per year. Fraction of organic material buried at the lake bottom of 10% as described by Meyers and Ishiwatari (1995) to be a medium range for a lake of this depth. Carbon to hydrogen ratio in the organic matter were taken from the Redfield ratio (Redfield, 1958). The simplification of the reaction model to an oxidizing reactor is valid only as long as the external C_{org} input into the lake is not significantly raised. Otherwise, reducing conditions in the hypolimnion and alkalinity producing reactions such as sulfate reduction as well as vertical gradients due to stratification must be considered. The reduction to a zero-dimensional system is based on the assumption that effective parameters for gas exchange and precipitation can be used. The precipitation of another solid phase apart from ferrihydrite that was used in all of the scenarios affects the magnitude of acidity release. The precipitation of 1 mol Ferrihydrite can potentially release 3 mol H^+. The precipitation of 1 mol Schwertmannite can, for example, potentially release 2.63–2.75 mol H^+, depending on the sulfate content.

5. Conclusions

The conclusions drawn from this investigation are:

1. the local groundwater flow system dominates the acidity influx into the lake; and
2. the recreational area Lake Senftenberg is most likely to undergo a degradation in water quality as a result of the flooding of the mines in its vicinity.

The planning of water quality goals for the large number of lakes that will establish in the area in the next few years has to take into account the local groundwater flow systems. Sustainable decisions and remedial actions must be oriented on the hydrologic framework. The water quality in Lake Senftenberg could be influenced by inducing reactions in the aquifer to avoid exfiltration of groundwater with high iron concentrations. This remedial strategy was recommended for further investigation.

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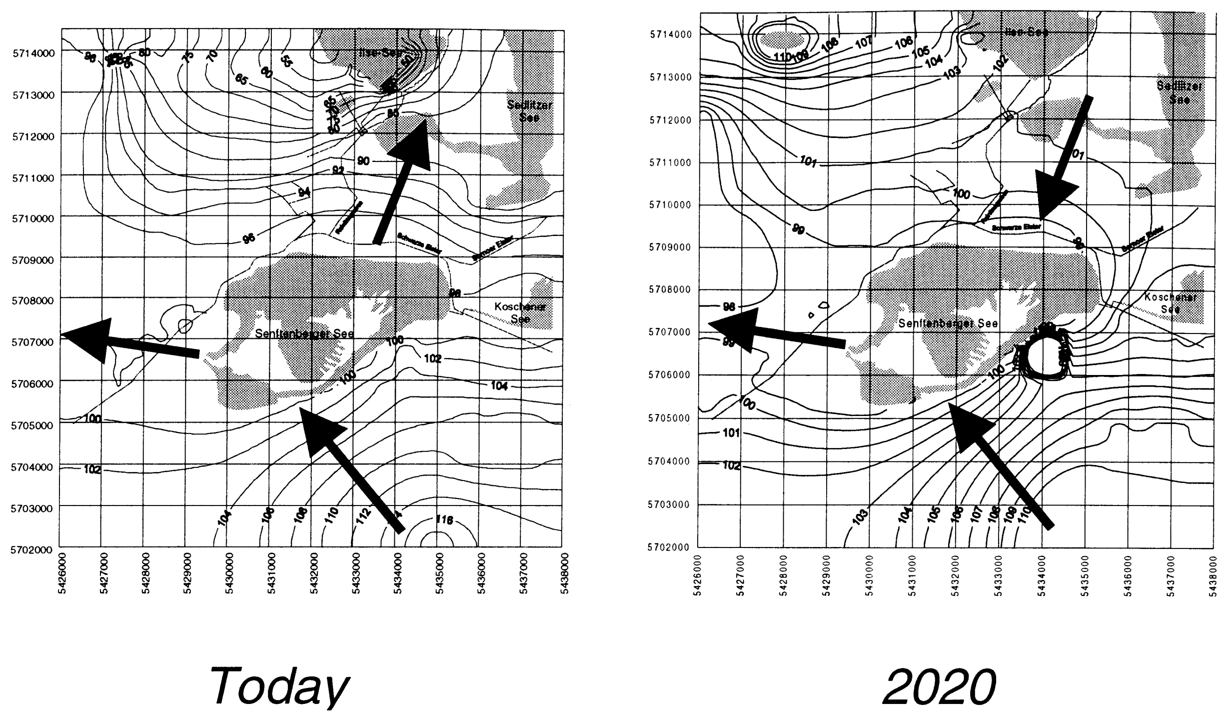

Fig. 9. Hydraulic heads (*m* above mean sea level) at the groundwater surface calculated with a 3-D groundwater flow model as influenced by the flooding of the open-pit mines in the north. Arrows indicating flow direction. Shore lines of the lakes at the northern boundary are not valid for the present time.

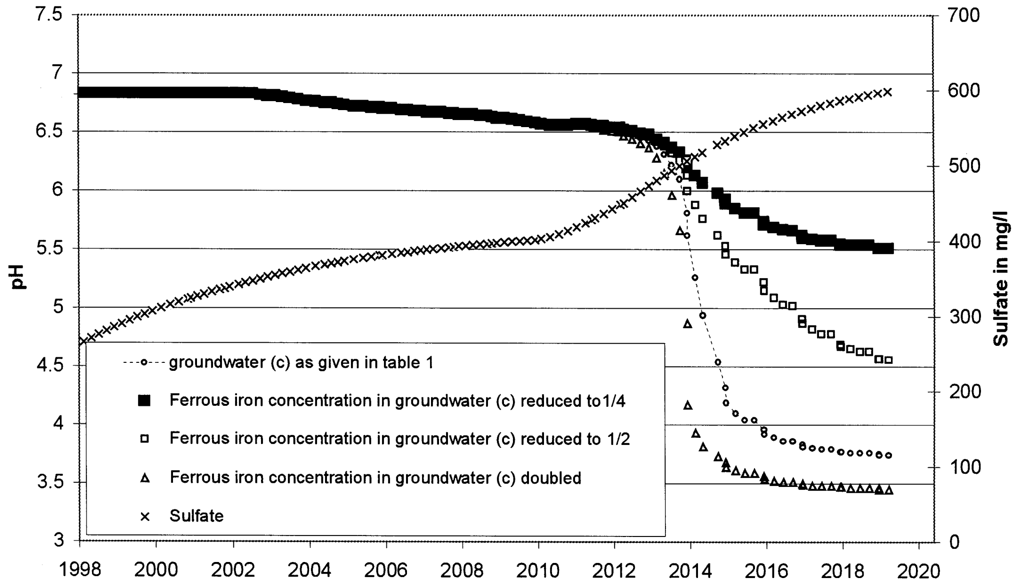

Fig. 10. Scenarios for different water quality of the groundwater inflow in the northern lake. Groundwater c refers to the same flux as described in Figs. 6 and 7 as well as Table 1.

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