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Technical Article

Implications of Predicted Hydrologic Changes on Lake Senftenberg as Calculated Using Water and Reactive Mass Budgets

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Abstract. Lake Senftenberg, Germany, is a post-mining lake that was flooded 30 years ago. It is anticipated that the levels of the surrounding post-mining lakes will rise, and that this will lead to a reversal of groundwater flow and consequently to an increase of acidifying groundwater flux into the lake. A tool to predict the future water quality of Lake Senftenberg has been developed. Present and future groundwater fluxes were calculated using a 3D hydraulic model of the surrounding aquifers. Oscillating hydraulic fluxes within the saturated and the unsaturated zones of the island within the lake, caused by continuous lake level changes, were calculated using a 2D sub-model. Mass fluxes into the lake from the aquifers, from the island, and from the River Schwarze Elster were determined by sampling or by laboratory experiments and were coupled with the hydraulic fluxes. The fluxes of acidifying components from the island sediments and sulfide oxidation products from drained zones were determined in laboratory experiments. Sediment erosion due to rill and gully formation after significant lake level change was calculated. The amount of acidifying compounds released from the eroded sediments was determined by laboratory experiments. The input of alkalinity due to the sedimentation of biomass was estimated. Gaseous partial pressures and mineral phases were used to describe the geochemical boundary conditions of the resulting lake water.

Key words: Acid mine drainage, Niederlausitz post-mining area, sediment leaching, transport modeling, water management, water quality prediction

Introduction

The Niederlausitz mining district in eastern Germany is currently undergoing radical changes. In the 1980's, the area was part of one of the world's largest lignite producing districts, but in 1990, most of the open-pit lignite mining activity was shut down, so that only five out of about 50 mines remained operating. Extensive mining had created a huge groundwater cone of depression (Figure 1). The water deficit for the Lausitz district in 1990 was estimated to be 9 billion m^3 of groundwater, including 4 billion m^3 of remaining open pit space that will form lakes.

Water management was centralized in the government-owned mining company and groundwater extraction measures of the individual mines were combined into a regional water management network. Groundwater flow modeling became necessary for decision making. The porosity and hydraulic conductivity parameters were defined for a large area model covering the entire Niederlausitz district, and local sub-models were refined with horizontal 500 x 500m and 125 x 125m grids using the finite volume simulation code GEOFIM (Both et al. 1990).

The mining administration agency Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft (LMBV) was formed to plan and conduct the remediation of the water deficit. Replenishment of the water deficit by natural groundwater recharge was estimated to be so slow that it would take around a century to re-establish natural steady-state flow. In most places, pre-mining groundwater levels could not be set as remediation goals, because urban development had occurred during the mining period in areas of formerly higher groundwater table. Therefore, a "near-natural, self-regulated water budget (hydrologic system)" approach was chosen. A total lake volume of $2.2*10^9$ m^3 will be added by the flooding of 40-50 separate lakes. The distribution of the surface water and the interconnection of the lakes are key questions. Additionally, potential impacts of the hydrologic changes on water quality are not only a problem specific to Lake Senftenberg, as described in this paper, but also must be considered for most lakes in the area.

To achieve rehabilitation in a time period of decades and to minimize soil mechanics and water quality problems, it was decided that water from the rivers Spree, Schwarze Elster and Neiße would be used to eliminate the cone of depression and refill the pits.

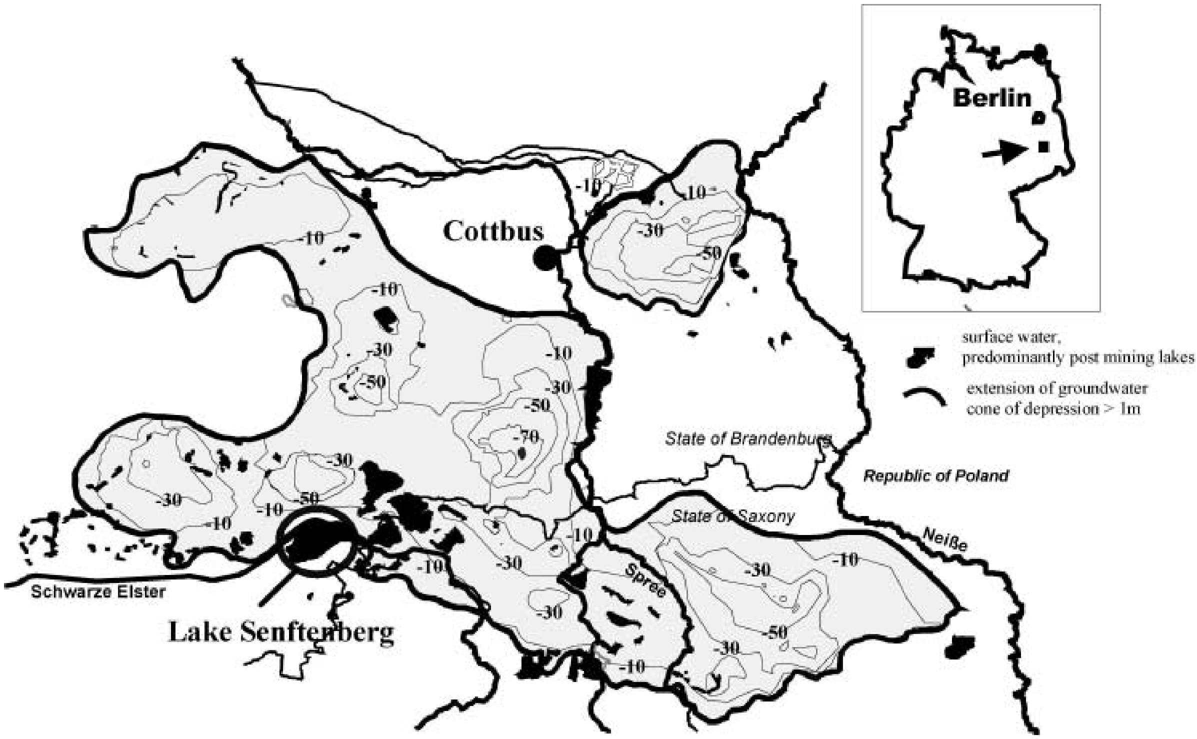

Figure 1. Groundwater cone of depression in the Niederlausitz mining district located about 100 km south of Berlin, Germany. The approximate area shown is 70 x 60 km (LMBV 2001).

Most of the construction and grading to provide suitable shorelines has been completed during the past ten years, and a number of lakes are already being flooded. Most lakes will reach their final water levels before 2005, though some will not be filled until about 2015. However, problems are generated first, due to landslides occurring on the slopes of the overburden dumps during the rewetting of the sediments, and second, due to degradation of water quality from acid mine drainage.

The latter problem arises because the Tertiary (Miocene) lignite seam and its overburden contains pyrite and marcasite, and so acid-producing materials are present in the unsaturated overburden dumps. Leaching from runoff and from groundwater passing through these dumps transports ferrous iron and aluminum into the surface waters, where oxidation and precipitation cause the familiar effects of acid mine drainage. Flooding pits with surface water counters acidification by importing alkalinity and by cutting down groundwater inflow into the rising lakes. Whether this is a sustainable measure strongly depends on the local hydrogeologic setting, the interaction of the surface waters with ground water and the water management strategy. The local hydrogeological setting is controlled by a number of factors, of which the regional flow system and the geochemical material properties are the most important. Our objective was to provide a water management tool that takes into account regional groundwater and surface water flow as well as hydrochemical reactions, and that can be used in the decision making process during rehabilitation. The quantity of surface waters is limited, and therefore using them to flood mines potentially creates a conflict with other surface water users in the area. Therefore, the use of surface water to flood mines must be well justified.

In this study, all of the acid sources were added to determine the overall effect on the lake. First, the hydrologic budget was determined using a groundwater flow model. Second, the water quality of the ground and surface water fluxes was determined. Finally, further mass fluxes into the lake due to the leaching of bank sediments and to biological production were quantified.

Site description

Besides the large number of post-mining lakes that are in the process of being flooded, the Niederlausitz area also contains a smaller number that were flooded in the past. One of them is Lake Senftenberg (Figure 2), which was flooded 30 years ago using water from

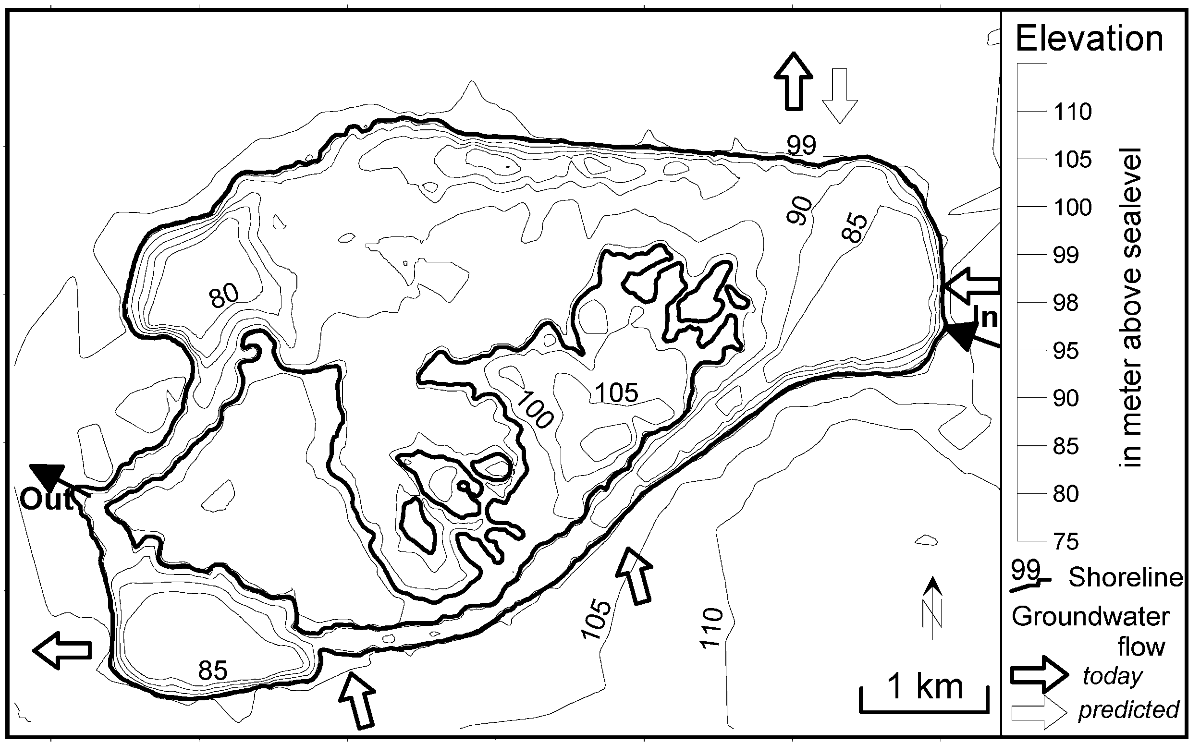

Figure 2. Elevation map of Lake Senftenberg. The bold line indicates the mean water level.

the river Schwarze Elster. The lake is connected to the river by a bypass channel, and is used as a retention pond to regulate river flooding. Its mean water level is 99 m above sea level and total volume is about 74 million m^3.

An island separates the lake into northern and southern parts, respectively about 60 million m^3 and about 14 million m^3 in volume. The island is constructed of overburden material that was dumped using a conveyor bridge, a technique that creates a fair amount of mixing of the overburden sediments (Figure 3). A chain of buckets delivered the overburden sediments from the excavator to the conveyor bridge, which dumped the material down a single chute. Although mixing is believed to be effective on a large scale (Berger 2000), little is known of the effects of the distribution of material on the release of acidity (Gerke et al. 1998).

The water quality differs significantly between the two parts of the lake. The northern part is neutral (pH 7) with an alkalinity of around 0.4 $mmol*l^{-1}$ and a sulfate concentration of 2.3 $mmol*l^{-1}$. The southern part is acidic (pH 3.5) with an acidity of 0.5 $mmol*l^{-1}$ and a sulfate concentration of 2.9 $mmol*l^{-1}$.

Hydraulic model

A 3-dimensional groundwater flow model was set up to calculate fluxes between groundwater and Lake Senftenberg. The code PCGEOFIM (Program for the Computation of Geofiltration and Migration: Both et al. (1990)) was used. The lake and rivers were modeled using the surface water option, which uses coupled boundary nodes and an external water budget for the surface water. The model elements that are connected to the lake are specified (Figure 4), and the fluxes that cross them summed and added to the lake volume. A "filling curve" function that relates water level and volume of the lake is then used to calculate the new water level of the lake. Based on the updated water level, new fluxes are calculated. The river option uses the down-stream water flux (user-input-boundary condition) to calculate a river head based on a steady state flow equation incorporating the geometric properties of the river bed. In a second step, this calculated head is used to calculate the interaction with the groundwater. This iterative procedure assures that infiltration and exfiltration rates will not reach impossible values with respect to the amount of water that can pass through the river.

Based on the output of the groundwater flow model, a simplified water budget of the lake was determined by creating groups of elements that deliver recharge or discharge to the lake (Figure 4). The northern part of Lake Senftenberg receives water from the river Schwarze Elster as well as from groundwater from the east; it discharges into the river and by groundwater leaving the lake in a northwesterly direction. These fluxes are calculated using the flow model (Table 1). Balance area c shows a zero influx because under present conditions it is an area of outflux from the lake. However, in 2015, it will receive groundwater due to the changing hydrological conditions.

To calculate a mass budget for each hydraulic flux, water quality parameters must be assigned. The concentrations of all chemical components were estimated based on the analysis of samples from balance areas a, c and d. The flow model predicts a reversal of groundwater flow in the area north of Lake Senftenberg (balance area c) due to the formation of new post mining lakes there. However, the quality of the groundwater recharging from balance area c in the future cannot currently be analyzed because the aquifer is not yet fully saturated. Therefore, the concentrations of chemical components were estimated and subsequently varied to investigate the sensitivity of the system to different estimated values.

Mass flux from the island

Besides the mass flux transported by groundwater, additional mass fluxes were considered due to

Figure 3. The former mine during operation (from Rösler and Noack 1993), with kind permission of Geiger Publisher, Germany).

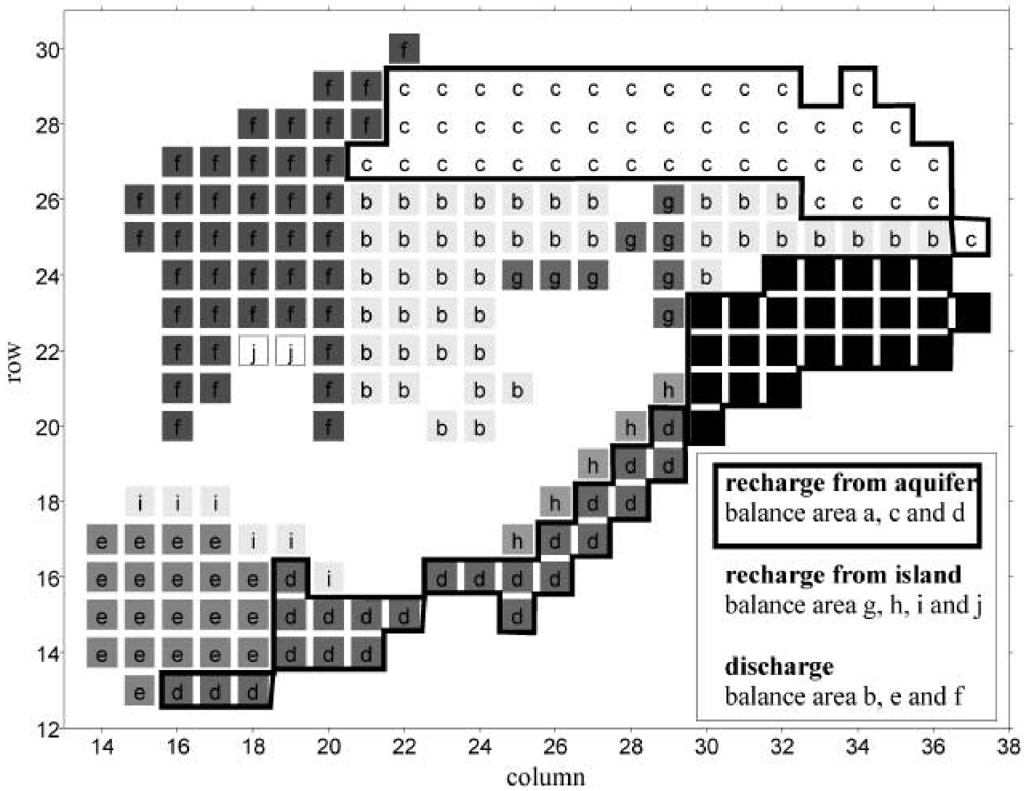

Figure 4. Balance areas around Lake Senftenberg and their representation as model elements. Each element represents an area of 250 x 250m. The actual geometry of the lake can be seen in Figure 2.

Table 1. Fluxes from model balance areas into Lake Senftenberg. The year 2015 represents steady state flow conditions in the post mining area. The gradual change in flux and water quality from the year 2000 to 2015 is part of the calculation.

input from	2000	2015
	m^3*yr^{-1}	m^3*yr^{-1}
Balance Area a	1.05E+06	2.26E+06
Balance Area c	0.00E+00	4.26E+06
Balance Area d	1.05E+06	1.16E+06
Central Island (g,h,i,,j)	4.21E+05	4.21E+05
River Schwarze Elster	2.10E+07	2.10E+07
River Drainage (c)	2.63E+06	1.47E+06

leaching of the island sediments, mass input by erosion along the shoreline of the island, and alkalinity input due to sedimentation of biomass. The impact of the island on the lake water quality was subdivided into two processes:

- Continuous leaching of the sediments in the unsaturated zone and leaching of the near shore aquifer by oscillating groundwater flow due to changes in lake level.
- Leaching of sulfide weathering products during prolonged low lake levels.

The second investigation was performed because a year-long low lake level combined with reduced water influx from the Schwarze Elster resulted in a complete loss of alkalinity and a drop of the pH to 4.5 in parts of the northern lake. This event was used to test the model and to evaluate its accuracy.

Hydraulic submodel

The lake water level oscillates with a period of one year, resulting in alternating fluxes in the near-shore aquifer and an oscillating water table on the island. Consideration of this annual variation of lake level also requires consideration of several important factors for the water balance, including the lag time due to the transport of infiltration though the unsaturated zone, the rewetting of the unsaturated zone during lake level rise, and water storage in the unsaturated zone. The 2D-flow model HYDRUS 2D (Simunek et al. 1999) was used to calculate the hydraulic fluxes and the rates of change and amplitude of the water table because it calculates water transport and storage in the unsaturated and saturated zone. The parameters describing the hysteretic behaviour of the water saturation of the sediment during drainage and rewetting were determined in laboratory experiments (Table 2). Additionally, the hydraulic conductivity value was estimated from grain size distribution curves according to Beyer (1964). Groundwater recharge was estimated to be 3 $l*s^{-1}*km^{-2}$.

The 2D-model represents a cross section through the western half of the island. The boundary conditions are shown in Figure 5. Only the continuous oscillation of the lake level is important for the prediction because prolonged low lake levels will be avoided in the future. The model was tested for the scenario with a one-year low lake level by comparing the simulated results to the observed events. However, the description of those results is beyond the scope of this paper.

To set up the finite element grid, the HYDRUS-2D-mesh generator was used. The node to node distance was 4 m in the centre of the island and had to be reduced to 0.1 m in the vicinity of the groundwater table and the seepage face in order to resolve the changes of water content in the profile.

Continuous leaching of the island sediments

The first step was the calculation of the maximum depth of the unsaturated zone with continuous lake level change. The surfaces and their relation to the current lake water level are shown in Figure 6. The intermittently and permanently unsaturated area is assumed not to contain sulfides any more because of repeated, frequent transport of oxygen into the soil over the 30-year period. The water balance of the island is shown in Table 3.

The volume of water leaving the system comprises 12% originating from infiltrating lake water and 88% from groundwater recharge from the island. The island groundwater recharge creates a smaller subsystem of the areal flow system, which is incorporated in the larger saturated 3D-flow model. The 2D saturated-unsaturated model is bounded along the edge of the island flow subsystem. Its results are extrapolated to the actual size of the island by adjusting by the length of a simplified shoreline.

The quality of both groundwater and lake water components (Table 3) was determined in laboratory experiments. Lake water was filtered through a column of near-shore sediment at a calculated velocity of 0.05 $m*d^{-1}$ until no changes in pH and ionic concentration were measurable. The resulting water quality was expected to represent the lake after infiltration into the near-shore aquifer. Groundwater from the island that originated as precipitation leaching the unsaturated zone was sampled in the centre of the island and analysed directly. Both waters were mixed according to the 88:12 ratio noted above, as shown in Table 3, and added to the lake in the mixing step (as described below under "Calculation of lake water quality").

Leaching of sulfide weathering products during prolonged low lake levels

The maximum depth of the unsaturated zone after a low lake level for one year was calculated with HYDRUS-2D (Figure 5), and the resulting minimum groundwater level is shown in Figure 6. The output of the 2D-Model was converted to a simplified 3D geometry of the island, and the additional drained volume (Figure 6) of the sediment was calculated. This volume is assumed to retain some sulfides, which start to oxidise after the drainage has occurred. The amount of released sulfide weathering products was estimated from weathering experiments using sediments from the drained zone. The groundwater flow rate of about 0.05 $m*d^{-1}$ will transport solutes about 20 m per year. Therefore, the only weathering products released to the lake within one year are those from the near-shore part of the additional drainage zone. The sediment mass within this zone (Figure 6) along the shore was calculated as 2100 t. A pyrite weathering rate for this sediment was determined to $6*10^{-7}$ $mol_{Py}*m^{-3}{}_{Sediment}*s^{-1}$, which leads (Equation 1) to a yearly release of $9.2*10^{4}$ moles of protons.

$$FeS_2 + 15/4O_2 + 7/2H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \quad \text{Eq 1}$$

Table 2. Hydraulic model parameters for the 2D island profile. α and N are parameters describing the saturation according to Van Genuchten (1980).

Model-parameter	value
Residual saturation $[V_{total}*V_{water}^{-1}]$	0.03
Maximum saturation $[V_{total}*V_{water}^{-1}]$	0.35
k-value$_{saturated}$ $[m*d^{-1}]$	2.5
$\alpha_{wetting}$ $[m^{-1}]$	20
$\alpha_{drainage}$ $[m^{-1}]$	10
N	2.1

Table 3. Cumulative water balance for the island

	volume*year^{-1} *m$_{shore\ length}^{-1}$	volume*year^{-1} (whole island)	quota
Groundwater recharge +	48 $m^3*yr^{-1}*m_{shore}^{-1}$	380000 m^3*yr^{-1}	88%
Volume of infiltrating lake water =	6.5 $m^3*yr^{-1}*m_{shore}^{-1}$	50000 m^3*yr^{-1}	12%
Volume of exfiltrating water	54.5 $m^3*yr^{-1}*m_{shore}^{-1}$	430000 m^3*yr^{-1}	100%

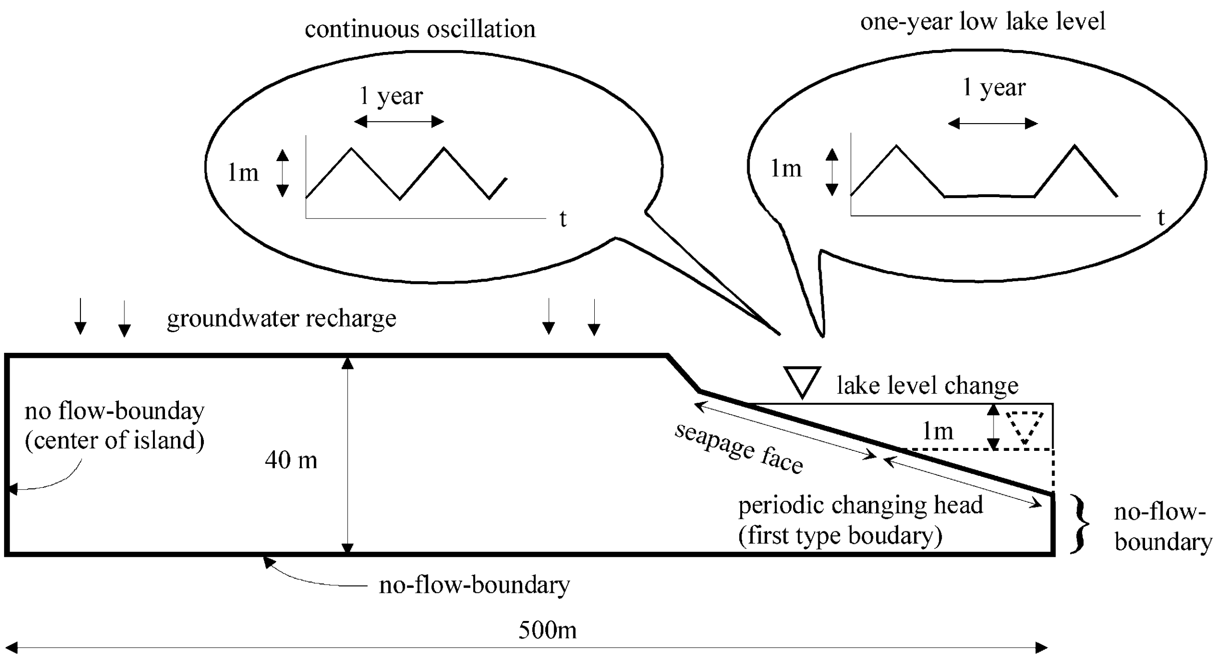

Figure 5. Boundary conditions of the 2D-model of the island cross-section

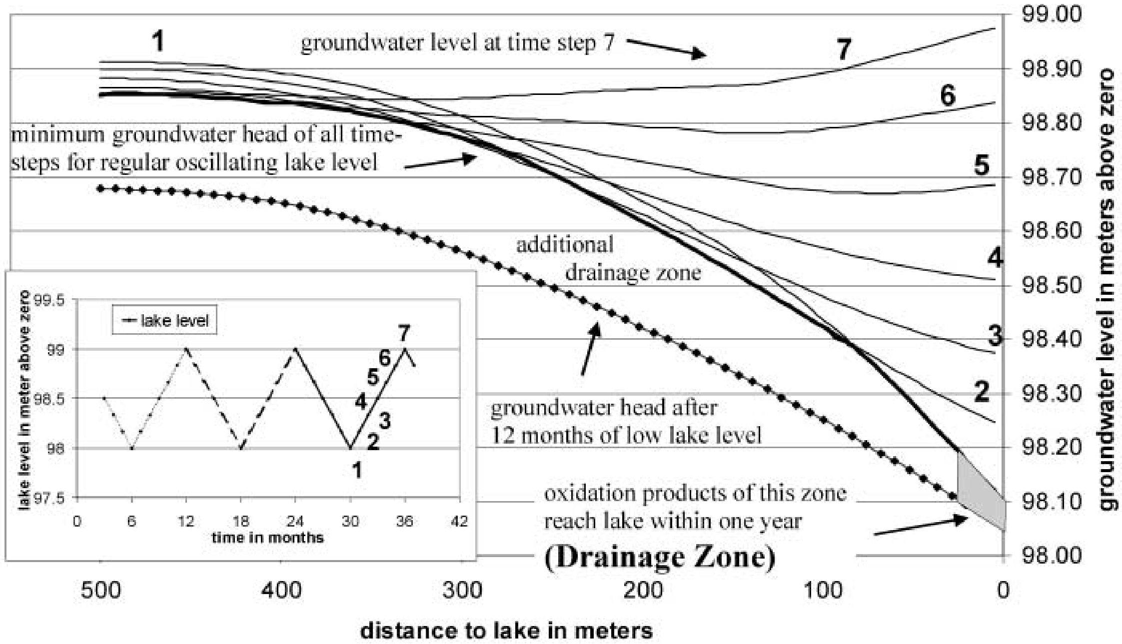

Figure 6. Various water levels and the resulting groundwater levels during continuous oscillation of the lake

The protons (H^+) released are buffered by iron and aluminium in the sediment. However, acidity in the pore water is transported not only by protons but also by Fe^{2+} and Al^{3+}, and its release is calculated on the basis of the aquatic element speciation. It depends on the pH, the element concentration and the mixing fractions in the lake. The total acidity of the discharging groundwater at pH 4 is, in addition to the protons, composed of $6*10^{-5}$ moles/l of Fe^{2+} and $1.1*10^{-4}$ moles/l of Al^{3+}. (To keep the charge balanced, sulfate is added). This acidic input was added into the lake reaction only for the calculation of the effects of low lake levels.

Erosion

The island consists of Tertiary overburden material containing sulfide minerals. The other shorelines are composed of Pleistocene sediments that contain no acid-releasing compounds in the layers above the lake level. Leaching of eroding material was therefore only investigated for the island dump material. Because these dump sediments form steep slopes and are not covered by plants, they are prone to erosion compared to the other shoreline sediments.

The mass flux into the lake by erosion was estimated in two steps:

1. Estimation of the transported mass into the lake per time by wave erosion of the embankments and by rill- and gully-erosion due to heavy rain events.
2. Laboratory measurements of ion release from the eroded sediment in contact with the lake water.

Estimation of the transported mass into the lake

If the lake water level keeps at its lowest for sufficient time, wave erosion will carve a steady-state profile into the exposed shore. Figure 7 shows three steps of forming a steady state profile. The amount of sediment that will be transported into the lake to achieve equilibrium was calculated from the amplitude of the waves, their wavelengths, the inclination of the shore and the type of the sediments (Figure 8) using an empirical approach (Wagner 1996), which is based on laboratory results and theoretical considerations.

The amount of sediment eroded by storm events is inferred from measurements in other post mining areas as about 0.01 $t*m^{-2}*yr^{-1}$. Because the vulnerable area of the island is $1.4*10^6$ m^2, 14,000 $t*yr^{-1}$ are assumed to erode. This erosional component of the mass flux is considered to be independent of the lake water level.

Laboratory measurements of ions released from the eroded sediment

It is assumed that the lake water elutriates the entire eroding sediment mass. Repeated elutriations of shore sediment with lake water in laboratory experiments were conducted to determine the amount of released acidity as well as the concentration increase for Fe^{3+} and Al^{3+} and the decrease of pH. The amount of ions released was summed, charge-balanced with SO_4^{2-}, and added to the lake in the mixing step (see "Calculation of lake water quality").

Biological activity

According to simplified equation 2 (Redfield 1958), the production of biomass leads to the reduction of protons (H^+) in lakes, but most of the biomass is then oxidised again (Meyers and Ishiwatari 1995) in the reverse reaction. If the reaction rates are the same in both directions, no change in the concentrations of the reactants in the lake occurs. However, if part of the biomass detritus is not oxidized but buried in the lake sediments, a continuous reduction of the reactants occurs, causing a continuous loss of protons or an increase of alkalinity.

$$106\ CO_2 + 122\ H_2O + 16\ NO_3 + 1\ HPO_4^{2-} + 18\ H^+ + \boldsymbol{E} \Rightarrow \langle \text{mass of algae} \rangle + 138\ O_2 \qquad \text{Eq 2}$$

E is the (solar) energy-input. Measurements in eleven lakes in Switzerland (Kummert and Stumm 1992) show net production rates of carbon from 82 to 422 g(C) $m^{-2}*yr^{-1}$. Babenzien et al. (1988, cited in Klapper 1992) give a rate of 97 g(C) $m^{-2}*yr^{-1}$ for the Stechlinsee. This rate is dependent on the nutrient input rate. In this study, the present authors assumed a bioproduction of 150 g(C) $m^{-2}*yr^{-1}$ for Lake Senftenberg, which seems reasonable for mesotrophic, natural lakes of a comparable size. Ten percent of this production rate is assumed to be buried

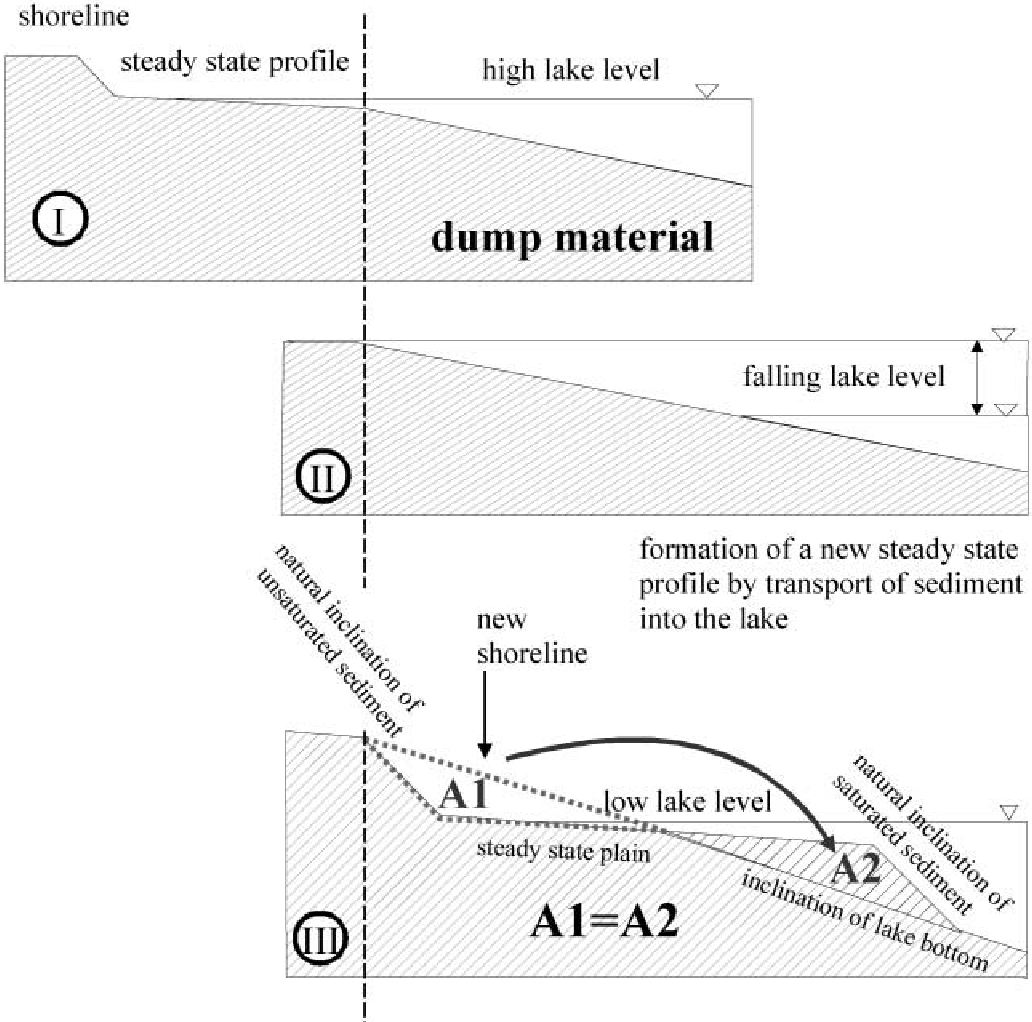

Figure 7. Formation of a new steady state profile by sediment transport into the lake during low lake level

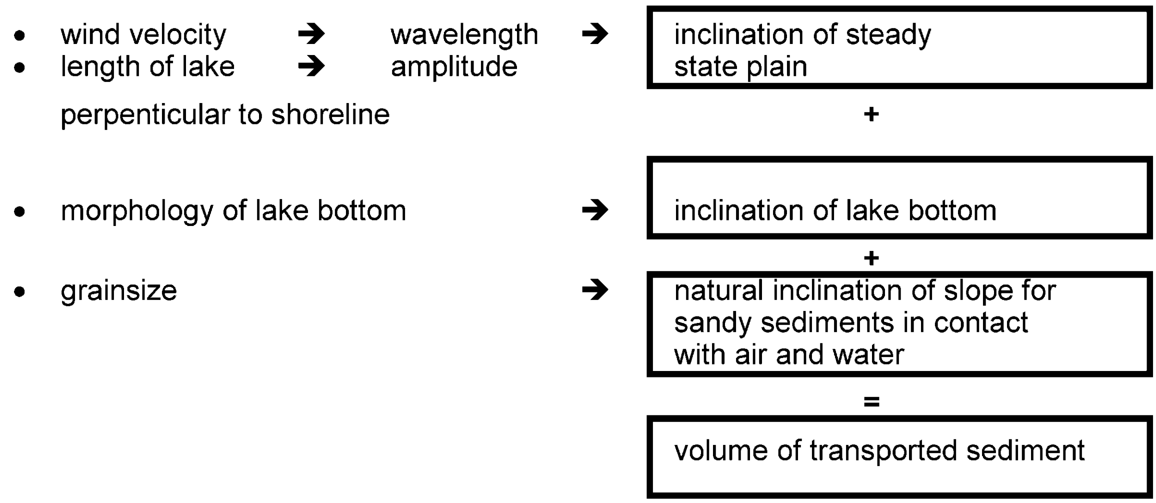

Figure 8. Scheme for calculating the mass of transported sediment at the lake shore

in the lake sediments. According to Equation 2, sedimentation of 5.9 mol C leads to a reduction of 1 mol H^+. The area of the northern part of the lake is about 5 km^2, resulting in total alkalinity production of:

$$5*10^6[m^2] * 15[g(C)*m^{-2}*yr^{-1}]/(12[g(C)*mol^{-1}]*5.9) = 1.06*10^6 \text{ mol } H^+ \text{ per year.}$$

In pH-neutral lakes, phosphate and nitrate limit bioproduction. In acid lakes, carbon can be the limiting factor because of the low levels of biological carbon in acidified waters. If the lake were to be acidified, the production of biomass would likely be limited by lower micro-organism activity, reducing the bioproduction by up to 50% at pH between 4 and 6. The actual C:N:P ratio of the biomass produced in Lake Senftenberg was not investigated and is expected to differ from that given by Redfield (1958), but in any case, the constituents of the biomass must be charge-balanced. Since the P and N species are anionic, they have to be counterbalanced by cations, which affects the proton balance.

Calculation of the lake water quality

Before combining all fluxes, each water from the balancing areas and from the island was put into equilibrium with atmospheric conditions using the program MINTEQ-A2 (Allison et al. 1991). Titrations were simulated to check the base- and acid-neutralizing capacity. In the reaction calculations, MINTEQ-A2 uses the parameter TOTH, which stands for "Proton Condition" (Stumm and Morgan 1996). The parameter describes the total concentration of H irrespective of the speciation. In neutral water, the major part of the TOTH is bound as inorganic carbon, as HCO_3^-. MINTEQ-A2 also has an option to allow the separate input of H-concentration; this was used to handle the protons consumed by the sedimentation of biomass.

After the dissolved compounds were balanced, the reaction of the various fluxes with the lake water was calculated. For this calculation, equilibrium with O_2 and CO_2 and the mineral ferrihydrite was assumed. In neutral and oxidized conditions, the dissolved Fe-concentration is very low. Whether ferrihydrite or goethite is precipitated is not of major concern; the acidity production is the same for both minerals. Schwertmannite releases 10% less acidity but was not used because very little sulfate was found in the sediments at the lake bottom.

The partial pressure of CO_2 in the lake is controlled by the inorganic carbon concentration of the influent groundwater and by the release of CO_2 into the atmosphere. A CO_2 equilibrium is assumed between the lake and the atmosphere and the measured dissolved inorganic carbon (DIC) concentration is assumed to represent the steady state concentration in the lake. To perform all speciation calculations in the lake water body at the dominant ambient CO_2 partial pressure, the latter was calibrated by inverse modeling to result in the measured DIC concentration. The constant value $2.6*10^2$ Pa is assumed for all calculations.

Lake Senftenberg is dimictic, and oxygen was measured in the hypolimnion throughout the year. An oxygen content of 90% saturation was derived from measured profiles and assumed to be constant.

Table 4. Hydraulic fluxes and transported alkalinity and acidity considered in the lake model.

	input from	Acidity/Alkalinity	rates 2000	rates 2015	input per time 2000	input per time 2015
		$mmol*l^{-1}$	m^3*yr^{-1}	m^3*yr^{-1}	$moles *yr^{-1}$	$moles *yr^{-1}$
Acidity	Source Area a	13.0	1.05E+06	2.26E+06	1.37E+07	2.94E+07
	Source Area c	8.0	0.00E+00	4.26E+06	0.00E+00	3.41E+07
	Source Area d	5.7	1.05E+06	1.16E+06	6.00E+06	6.60E+06
	Central Island	0.8	4.21E+05	4.21E+05	3.37E+05	3.37E+05
	Rill and Gully Erosion		0.00E+00	0.00E+00	2.50E+04	2.50E+04
	sum				**2.00E+07**	**7.04E+07**
Alkalinity	River Schwarze Elster	1.2	2.10E+07	2.10E+07	2.52E+07	2.52E+07
	River Drainage	1.2	2.63E+06	1.47E+06	3.16E+06	1.77E+06
	Biological Processes		0.00E+00	0.00E+00	1.05E+06	5.26E+05
	sum				**2.95E+07**	**2.75E+07**

Results

The hydraulic model shows a reversal of the groundwater flow in the northern aquifer. In 2010 or 2011, Lake Senftenberg will receive groundwater recharge from the northern aquifer (balance area c). The present groundwater in this area is highly acidified and will reduce the pH in Lake Senftenberg after 2010. Leaching of the island's sediments does not contribute significantly to the acidification of the lake because the near-shore sediments do not release high amounts of acidifying substances. However, additional release of sulfide weathering products during prolonged low lake levels, together with a reduced input of freshwater by the river Schwarze Elster, leads to significant reductions of buffer capacity and pH in Lake Senftenberg. The calculated pH reduction was not as great as that measured during the long-lasting low lake level because the model output represents an average value for the whole northern part of the lake and does not simulate local minimum values. Also, the biological production of alkalinity is not considered to be strong enough to buffer the expected increasing input of acidifying groundwater. Table 4 shows all fluxes both for the present and for after the reversal of the groundwater flow in the north of the lake. The total alkalinity input currently exceeds the acidity input, but after flow reversal in the north, high inputs of acidity will dominate lake water quality.

Acknowledgments

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