Integrated Methods in Catchment Hydrology—Tracer, Remote Sensing and New Hydrometric Techniques
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Water and component mass balances in the catchment of Lake Stechlin

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Abstract Surface water and groundwater are hydraulically connected in the Lake Stechlin catchment. Therefore, there is an urgent need to study unsaturated and saturated flow and related major ion transport processes and exchange with the surface water to analyse the influence on the aquatic chemistry, especially on calcite precipitation in the lake. Based on long-term measured hydrological data, in an integrated approach a steady-state regional groundwater model was developed and fluid mass balances were calculated. Chemical analyses show higher concentrations of major components (Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe_{tot}, Cl^-, SO_4^{2-}, NO_3^-, HCO_3^-) in groundwater than in lake water. Based on the computed subsurface water balance it can be deduced that groundwater has a strong influence on the composition of the surface water, especially for Ca^{2+} and HCO_3^-.

INTRODUCTION

Lake Stechlin is one of the main research areas of the Institute of Freshwater Ecology and Inland Fisheries, Germany. It is located near the boundary between Brandenburg and Mecklenburg-Vorpommern, 130 km north of the city of Berlin. In order to complete the research on the hydrological balance of the entire catchment, studies on the quantitative and qualitative conditions in the subsurface were initiated. Lake Stechlin has no inflow from streams or rivers; it is a groundwater lake, typical of the northeast German landscape. Thus there can be a major influence of groundwater on surface water and an important effect on chemical and ecological processes in the Lake itself (Hartmann, 1996; Koschel, 1997; McConnaught *et al.*, 1994). Mass balances for fluid in the catchment have been used to set up a groundwater model. From this, the input of dissolved components related to calcite transport from the aquifer into the lake could be estimated. The objective of the present paper is to quantify the influence of the subsurface catchment water on the lake in order to decide if groundwater plays an important role concerning calcite oversaturation and precipitation in surface water. Calcite precipitation can be observed regularly in Lake Stechlin and affects the trophic state of the lake—a phenomenon which is well-known from other lakes as well (Lake Erie, Lake Constance).

DESCRIPTION OF THE CATCHMENT

Lake Stechlin and its catchment (Fig. 1) is a part of the Northern (Baltic) Land Ridge which was formed in the latest glacial period—the Weichselian. The catchment of Lake Stechlin and Lake Nehmitz is mainly formed from the "Frankfurter" and locally the "Fürstenberger" stage (Marcinek, 1981). The Lake Stechlin area, like other glacial-borne regions, had no natural surface discharge. It drains to the River Havel; there are two aquifers which are separated by a 10–30 m layer of boulder clay (Fig. 2). The unconfined aquifer consists of fluvioglacial deposits (outwash plain of the "Fürstenberger Staffel" and the "Pommersches Stadium"). Both the unconfined aquifer and the surface water belong to the same hydraulic system. The lakes are fed by groundwater from the unconfined aquifer (Ginzel & Handke, 1995).

The extent of the groundwater catchment of Lake Stechlin results from measurements of the groundwater and surface water levels at 50 groundwater observation wells and 16 surface-water observation points. These measurements enabled us to construct the groundwater level contours and the subsurface water divides (Fig. 1). On the basis of these measurements and findings, a regional two-dimensional model based on FAST-code (Holzbecher & Ginzel, 1998) was constructed which is described below.

RESULTS

Water balance and numerical model

Lake Stechlin has an area of 4.25 km^2, a mean depth of 22 m and a volume of 96.88·10^6 m^3 (Krey, 1985). The catchment encompasses a land surface of 12.57 km^2

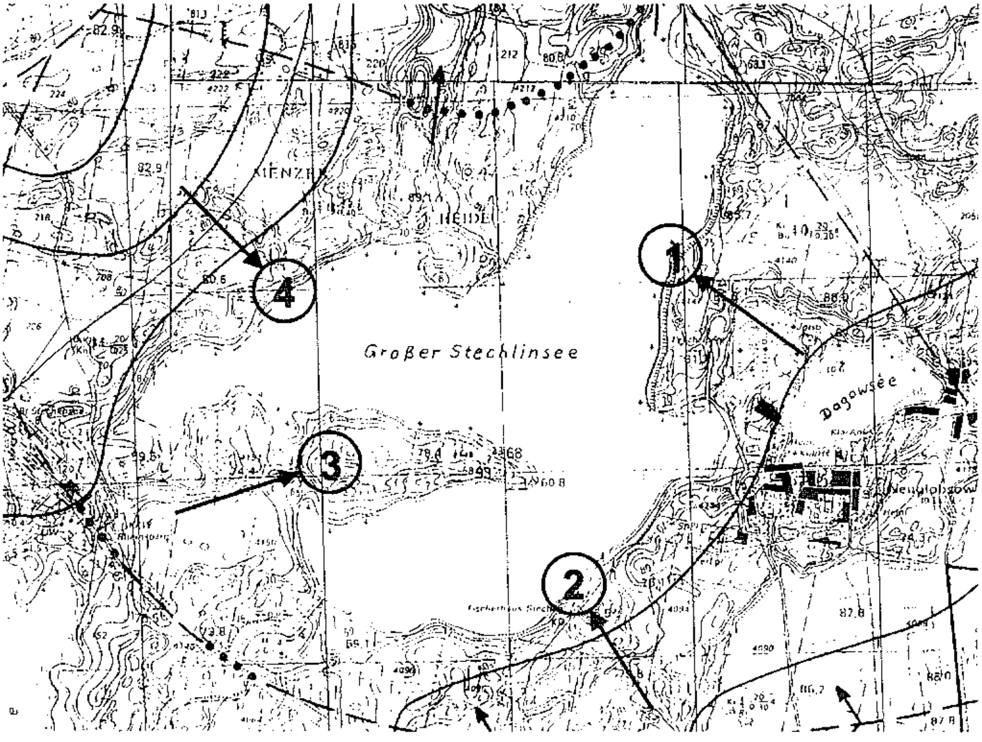

Fig. 1 Map of Lake Stechlin and its catchment area (equipotential lines, measured in 1995).

and a near-surface groundwater layer at a depth of 20–40 m. The total volume of water in the subsurface catchment is between $62.5 \cdot 10^6$ m^3 and $125 \cdot 10^6$ m^3 depending on the depth of the aquifer and calculated with a mean value for the effective porosity of sands ($n = 0.20$), typical of the region.

A detailed study on meteorological conditions and its relationship to the water budget for Lake Stechlin and the adjacent Lake Nehmitz was published recently by Richter (1997). The study is based on monthly measurements from 1952 to 1995 which show short-term (annual) and long-term fluctuations of precipitation, evaporation and water levels.

Mean annual precipitation in this period is 654.3 mm and evaporation per unit of lake area is 725.6 mm. Evaporation and evapotranspiration of land surface amount to 505.5 mm. Measured long-term discharge from the lake is 523 mm related to the lake area. As the long-term storage of the surface water is nearly zero (–0.2 mm), it is justifiable to regard the lake as a steady reservoir with a mean value balance:

$$P + Q - E - D = 0 \tag{1}$$

with P = precipitation, Q = groundwater inflow, E = evaporation, D = discharge.

Three of the four variables in the equation are known from measurements. The fourth, the exchange term between surface water and groundwater Q, can be calculated. Using the values of Richter (1997) one obtains $Q = 594.1$ mm. This value is related to a lake surface unit and has to be adjusted when a balance is made in relation to a land surface unit. In the long term, the groundwater storage of 0.1 mm is negligible. The aquifer can be regarded as steady in a long-term water balance. Therefore, it is reasonable to work with a steady-state model as an approximation of

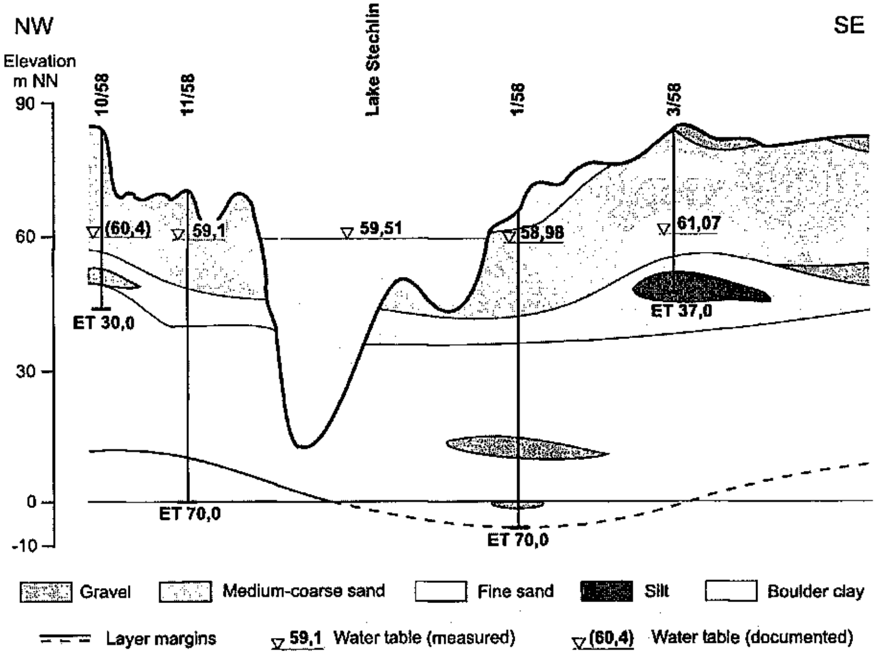

Fig. 2 Geological/hydrogeological cross-section.

the real situation. Under steady-state conditions, groundwater recharge is equal to Q, the groundwater discharge into surface water.

The value for groundwater recharge of 4 l s^{-1} km^{-2} has been adopted from the lysimeter station in Eberswalde-Britz, where geological and meteorological conditions as well as the vegetation (beech, oak and pine forest) are similar to those of the Stechlin area (Lützke *et al.*, 1980). The given a value for recharge equal to 125 mm per unit surface which is slightly less than the value of Richter (1997) given above.

A two-dimensional steady-state numerical model was set up to provide a picture of the subsurface flow pattern. The model area extends from the shorelines of Lake Stechlin and Lake Dagow to the watershed boundaries (see Fig. 3). In the computer model, the aquifer is divided into 1257 blocks each with 100 m × 100 m horizontal surface area. Hydraulic conductivity is assumed to be isotropic and homogeneous with a value of $1.0 \cdot 10^{-4}$ m $year^{-1}$ s^{-1}. In each block an inflow with a source rate of 4 l s^{-1} km^{-2} (representing homogeneous groundwater recharge) is considered. This is equal to 125 mm natural recharge per unit land surface and equivalent to a total annual flux of $1.57 \cdot 10^{6}$ m^{3} $year^{-1}$.

At the outer boundaries of the model, at the watershed divide, no-flow conditions are set. However, temporary groundwater discharge at the northern shore of the lake was observed, for example in summer 1995, as depicted in Fig. 1. At both interior boundaries, at the shorelines, Dirichlet conditions with prescribed hydraulic head are required. As values the long-term average of the lake water levels are prescribed: 59.6 m a.m.s.l. for Lake Stechlin and 60.3 m a.m.s.l. for Lake Dagow.

As modelling software, the FAST-A code (Holzbecher, 1996) was used. FAST-A calculates hydraulic heads in the interior of all model blocks. Calculated values were

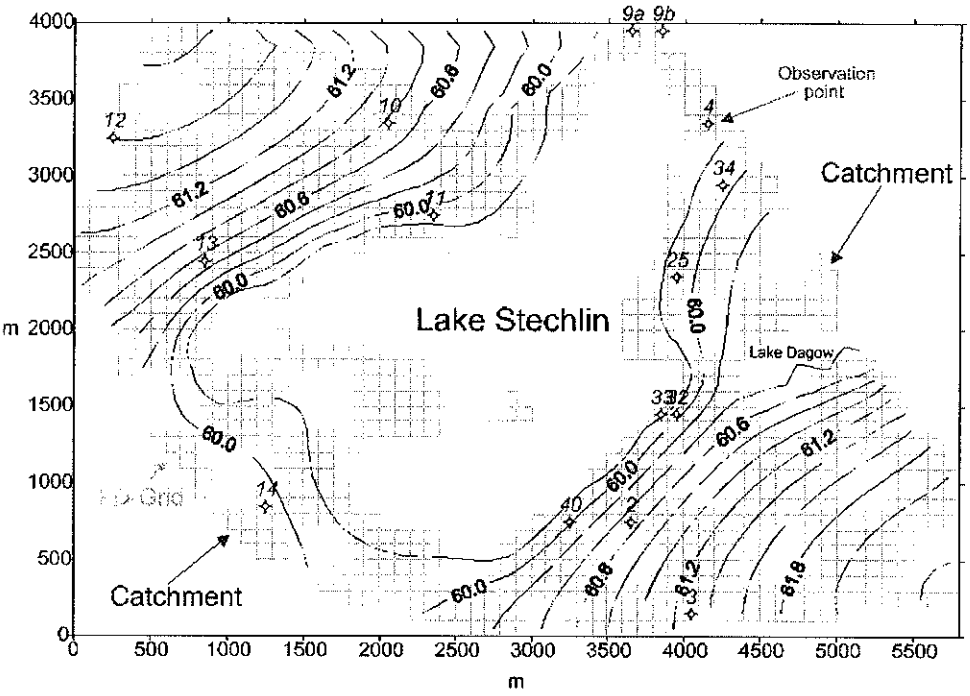

Fig. 3 Finite grid, observation points and isopotential contours calculated with FAST-A.

compared with means of measured values of long-time observation wells at 15 representative locations (see Fig. 3). In a calibration procedure, the aquifer depth was varied in order to minimize the deviations between measured and calculated values (criterion of least squares, see: Holzbecher & Ginzel, 1998). The calibration procedure produced finally an aquifer depth of 21.5 m. The maximum deviation between modelled and measured heads is 1.2 m, the mean deviation is 4 cm. Figure 3 depicts the hydraulic head distribution in the aquifer for the calibrated model.

With a mean aquifer depth of 21.5 m, the total volume of water in the catchment amounts to $67.57 \cdot 10^6$ m^3. The volume of the subsurface saturated water reservoir connected to the lake is $54.05 \cdot 10^6$ m^3. The surface water reservoir is greater but in the same order of magnitude. Using the value for long-term groundwater recharge Q, the mean residence time in the aquifer is found to be 34.4 years. The variation of individual residence times is great: a water molecule entering the subsurface water body near the shore will soon move into the surface water, while a particle infiltrating near the watershed takes a long time to reach the lake. A detailed picture of travel times from various parts of the aquifer is produced by the Shl_Path post-processor. In Figure 4 the flow field is depicted for the entire basin of Lake Stechlin. Streamlines into the aquifer are traced, starting at locations at the lake shore. Markers are shown in 10 year travel-time distance. The maximum number of markers along a streamline is restricted to 5. Otherwise, markers tend to fill the area when the zero-velocity boundary at the watershed is approached.

Using a zoning approach, a more detailed view of groundwater discharge in the catchment is obtained. From the eastern end-moraine (see ① in Fig. 1) 23.5% of total water flow enters Lake Stechlin. Main contributors are both northwest and southeast fluvioglacial deposits (② and ④ in Fig. 1) with 36.5% and 21.7%.

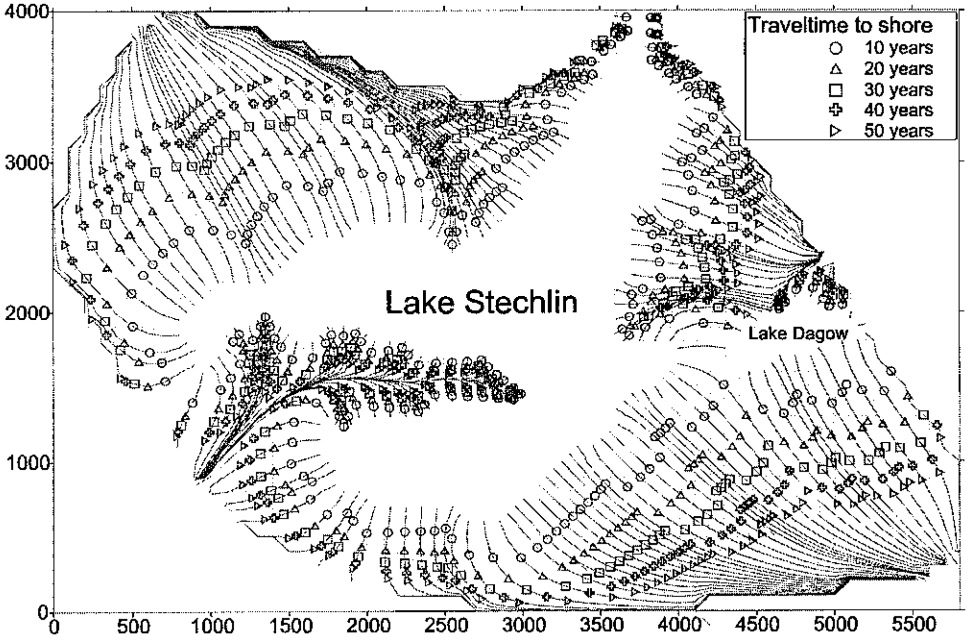

Fig. 4 Flow lines in the aquifer, marks after 10 years travel time, starting at the shore.

From a hydrogeological point of view, these are characterized by a boulder-clay base and long flow paths, and from a topographical view, by steep gradients. Ten per cent of the groundwater discharge originates from pure fluvioglacial deposits (③ in Fig. 1) with low topographic gradients and short flow paths on the western shore. While Lake Stechlin has no subsurface outflow, there is groundwater recharge in the western part of Lake Dagow. The net water balance of Lake Dagow amounts to 8.3% of total fluid flux.

Component mass balance

The calcite–carbon equilibrium in subsurface water is influenced by CO_2 partial pressure of the gaseous phase in soil/unsaturated zone, exchange conditions between gas and water phases, calcite concentrations in sediments, temperature and groundwater flow velocities and residence times (Merkel, 1992; McConnaught *et al.*, 1994). Chemical equilibrium and associated reactions of a subsurface calcite–carbon system are described by Hartmann (1996), discussing the main compounds in soil water and groundwater.

The data of concentrations (Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe_{ges}, Cl^-, SO_4^-, NO_3^-, HCO_3^-), temperature, electric conductivity, pH, acid capacity and CO_2 concentration from different groundwater boreholes compared with surface water are given in detail in Hartmann (1996). For all ions (except for K^+) concentrations in groundwater are about 130–220% higher than in lake water. Both water bodies are in a state of calcite-saturation at different levels, which was supported by results of geochemical modelling using PHREEQE (Parkhurst, 1980). Considering CO_2 and Ca^{2+} concentrations in different boreholes along a flux-oriented transect, see Table 1, it seems to be plausible that calcite precipitation in the subsurface takes place along this flow path.

For quantifying the influence of groundwater on Lake Stechlin, first, annual load was calculated based on the computed groundwater balance as described above. Assuming that ion concentrations of groundwater are equal in different parts of the catchment, calculation of subsurface contribution to the lake is based on an annual flux of $1.57 \cdot 10^6$ m^3 $year^{-1}$, which differs slightly from former investigations of Hartmann (1996). In Table 2 main ion loads from subsurface and atmospheric compartments and the lake inventory are shown, demonstrating the principal influence of groundwater.

Considering the ratios between groundwater and rainfall, more than 95% of components reaching the lake originate from the subsurface. But these ion loads represent only 1–3% of the entire lake inventory with the exception of $CO_{2(aq)}$. Based on the computed subsurface water balance Table 2 shows that groundwater from the catchment acts as a source, especially for Ca^{2+} and HCO_3^-, and is thus a driving force for continuous calcite precipitation.

Assuming that the annual fluxes into the lake from groundwater and the atmosphere are approximately constant, the residence time for different ions in the lake has been calculated dividing the inventory through the inflow. The results are shown in Table 3.

Taking into consideration all the measured ions in the different compartments (rain, groundwater inflow and outflow, lake) a positive mass balance of the Lake Stechlin is found. But if evaporation of the lake itself is to be taken into consideration as a negative balance term, an "oversaturation" of Ca^{2+} and HCO_3^- in the lake is

Table 1 Comparison of $CO_{2(aq)}$ and Ca^{2+} in different groundwater observation points (distances are measured from borehole to lake).

	Borehole 1 (1000 m distance)	Borehole 2 (250 m distance)	Borehole 3 (25 m distance)
Thickness of the upper sandy layer (m)	25.61	11.20	5.58
$c(CO_{2(aq)})$ in 10^{-5} (mol l^{-1})	21.9	17.6	37.0
Saturation index (calcite)	0.05	0.23	0.04
pH	7.58	7.70	7.43
$c(Ca^{2+})$ (mmol l^{-1})	83.50	90.00	102.00

Table 2 Ion loads (groundwater and rainfall) and lake inventory.

Component	Upstream groundwater load (t $year^{-1}$)	Rainfall load (t $year^{-1}$)	Lake inventory (t)
$[Na^+]$	17.15	0.84	811
$[K^+]$	2.80	0.41	278
$[Ca^{2+}]$	147.90	1.07	4600
$[Mg^{2+}]$	6.86	0.15	357
$[Cl^-]$	22.79	1.68	1037
$[SO_4^-]$	150.77	6.91	3793
$[HCO_3^-]$	317.41	0.00	11951
$[CO_{2(aq)}]$	21.46	1.89	214

Table 3 Residence times for main ions.

Component	Residence time (years)
$[Na^+]$	45.08
$[K^+]$	86.61
$[Ca^{2+}]$	30.8
$[Mg^{2+}]$	50.9
$[Cl^-]$	42.38
$[SO_4^-]$	24.05
$[HCO_3^-]$	37.65
$[CO_{2(aq)}]$	9.17

evident which leads to the well observed calcite precipitation and sedimentation.

CONCLUSION

Mass balance estimations for fluid and main chemical compounds are presented for Lake Stechlin, Germany, and its subsurface basin, in order to clarify the role of groundwater discharge into the lake concerning calcite oversaturation and precipitation, which can be observed regularly in the surface water. Elements of the mass balance have been calculated using an integrated approach, combining field measurements, chemical analyses and numerical modelling. The results show clearly that groundwater inflow is a driving force for continuous calcite precipitation in the lake.

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