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Mining lakes as groundwater-dominated hydrological systems: assessment of the water balance of Mining Lake Plessa 117 (Lusatia, Germany) using stable isotopes

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Abstract:

In the present study, the stable isotopes $\delta^{18}O$ and $\delta^{2}H$ were used for assessment of the water balance in a heterogeneously structured catchment area in the Lusatian Lignite Mining District, in particular, for estimation of the annual groundwater inflow and outflow (I_{GW} and O_{GW}) of Mining Lake Plessa 117. The application of stable isotopes was possible since the water exchange in the catchment area had reached steady-state conditions after the abandonment of mining activities in 1968 and the filling of the voids and aquifers by re-rising groundwater in the years thereafter. Diverging slopes of the Evaporation Line and the Global Meteoric Water Line manifested as evaporation from the lake catchment area. The calculated isotope water balance was compared with the commonly used surface water balance, which is unable to differentiate between I_{GW} and O_{GW}, and with a local groundwater model. The groundwater model calculated an I_{GW} of about 811 000 m^3 yr^{-1} and an O_{GW} close to zero, whereas the isotope water balance showed fluxes of about 914 000 and 140 000 m^3 yr^{-1}, respectively. Considering the contribution of the groundwater inflow to the total annual input into the lake (ΔI_T) and the mean residence time (τ), where the groundwater model and the isotope water balance calculated 42 and 47% for ΔI_T and 4·3 and 3·9 years for τ, respectively, it was shown that both water balance calculation methods led to comparable results despite the differences in I_{GW} and O_{GW}. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS mining lake; water balance; environmental isotopes; groundwater; groundwater model

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INTRODUCTION

In the near future, the Lusatian Lignite Mining District will have more than 200 lakes originating from mining activities. Strong acidification and artificial morphometry are the most important features distinguishing many of them from natural lakes of the region (Geller *et al*., 1998; Nixdorf *et al*., 2004). The oxidation of pyrite in aerated dump sediments (tertiary sands) within and near mining lakes generates acid mine drainage (AMD) rich in iron and sulphate (Evangelou, 1997). AMD has a decisive influence on the potential for use of abandoned mining lakes for other purposes, e.g. recreation or fishing.

Systematic understanding and prediction of the future development of mining lakes requires detailed limnological data on primary production (Lessmann *et al*., 2006), food web interactions (Wollmann *et al*., 2000), the quantification of matter and mass fluxes (Knöller and Strauch 2002; Knöller *et al*., 2004) and the interactions between groundwater and surface water (Hofmann and Lessmann, 2006). An exact knowledge of lake water balance, in particular of the amount of groundwater inflow and outflow (I_{GW} and O_{GW}) is therefore indispensable. Groundwater models can provide this information, but their application in geologically heterogeneous structured dump sites is accompanied by several uncertainties owing to the lack of distinct and high-resolution geological data, such as grain size distribution, pore volume, transmissivity or leakage coefficients.

In the last three decades, the stable isotopes of oxygen and hydrogen have been used with increasing frequency to calculate the water balance of lakes (Gat, 1970; Zimmermann and Ehhalt, 1970; Knöller, 2000; Gibson *et al*., 2002). The isotope method is a useful alternative to the established hydrological and geohydrological calculation methods and models. The stable isotopes method provides reliable estimates of groundwater inflow and outflow in lake water balance calculations. Recent studies have shown the practicability of this method for smaller lakes and catchment areas, e.g. Mining Lake 111 (Knöller, 2000; Gibson, 2001, 2002; Knöller and Strauch, 2002).

The main purpose of this study was to quantify the annual groundwater inflow and outflow (I_{GW} and O_{GW}) and, hence, to calculate the water balance of Mining Lake (ML) Plessa 117 based on the composition of stable isotopes occurring in the catchment area. Additionally, the isotope water balance was compared with the surface water balance and the established groundwater model for the region. The lake is considered to be a typical

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geologically, hydrogeologically and hydrologically disturbed landscape.

STUDY SITE

ML Plessa 117 (Grünewalder Lauch; 51°30′57″N, 13°39′46″E) is located in the former Plessa mining pit of the Lusatian Lignite Mining District in Germany. After the mine was abandoned in 1968, the lake formed and was filled with re-rising groundwater until 1972. Although acid mine drainage has resulted in high acidity (pH 3·1) and high electrical conductivity (up to 900 μS cm^{-1}), the lake has been used as a local recreation area since 1976.

The lake surface covers an area of 945 000 m^2. The maximum depth of 14·4 m is located in the north-east of the lake (Figure 1). The total water volume is 5 606 000 m^3 at a surface water level of 92·3 m a.s.l. Counteracting precipitation and evaporation in the catchment area lead to seasonal water level fluctuations of about 0·5 m.

ML Plessa 117, the largest lake of the region, is part of a chain of lakes linked by ditches that drain in the north–south direction into the river 'Schwarze Elster'. The lake receives surface water inflow from ML 118 in the west and feeds into ML 116 via an outlet in the south (Figure 1).

The groundwater table of the bordering aquifers is slightly above the surface water level. The main groundwater flow is directed from north to south. The lake shores are characterized by unclaimed quaternary aquifers. In contrast, the groundwater flow from the south-west passes areas mainly composed of tertiary dump material (Figure 1).

SAMPLING AND METHODS

In 2003, lake water samples were taken monthly from vertical profiles in steps of 2–4 m at the maximum depth in the north-east of ML Plessa 117 for isotope analyses. Additional water samples were also taken from the surface water inflow and outflow and from the precipitation sampler located on the western shoreline. Groundwater samples were collected twice (October 2002 and April 2003) from four wells (no. 41, 46, 3069 and 3070) located around the lake (Figure 1).

The isotopic composition of all water samples was determined at the Isotope Laboratory of the Centre for Environmental Research - UFZ, Germany by the chromium technique for ^{2}H and the H_2O–CO_2 equilibration method for ^{18}O with analytical accuracies of ±1·0‰ and ±0·1‰, respectively. The delta notation for ^{2}H and ^{18}O are relative to the Vienna Standard Mean Ocean Water (VSMOW).

All meteorological field data used for the water balance calculations, e.g. air temperature (T_{air}), precipitation (P) and relative humidity (h), were collected as hourly data obtained from Doberlug-Kirchhain, a nearby meteorological station (13 km north-west of ML Plessa 117) run by the German Meteorological Service (DWD).

The evaporation flux (E) of the lake surface was computed using LAKEoneD, an adapted one-dimensional

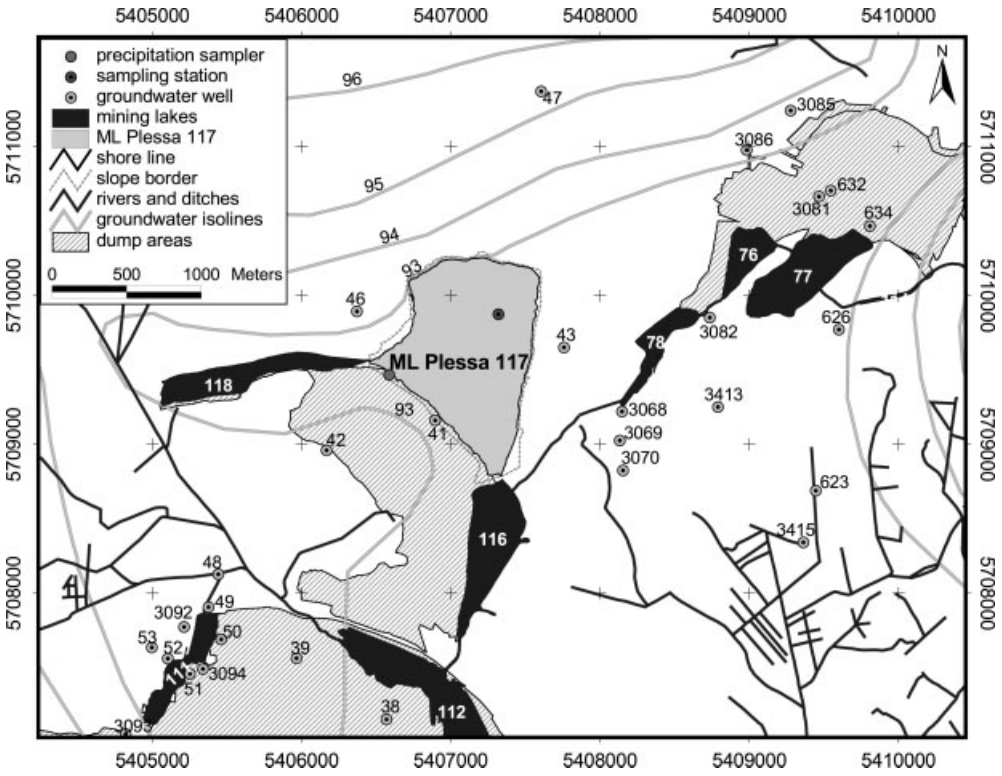

Figure 1. Research area of ML Plessa 117, showing sampling sites, groundwater table contour, dump sites and bordering mining lakes and ditches (coordinates in DHDN, Gauß-Krueger, 5th meridian)

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stratification model (Jöhnk and Umlauf, 2001; Hutter and Jöhnk, 2004; Jöhnk, 2005). The hourly data from the nearby meteorological station were therefore entered in the model and validated to the monthly temperature profiles of the lake (Hydrolab H20, Austin, USA or YSI 650, Yellow Springs, USA) over a 3-year period (2000–2003). The model ran with a vertical and temporal resolution of 0·5 m and 4 min, respectively. The so-called high-resolution surface water and air temperatures were used to calculate the evaporation flux, which was integrated to monthly values in 2003 for the water balance calculations.

The surface water inflow and outflow (I_S and O_S) was measured with an inductive discharge meter (OTT Nautilus C 2000, Kempten, Germany) three times in 2003.

Monthly changes in lake volume ($\mathrm{d}V/\mathrm{d}t$) were determined based on measurements of the lake surface water level in combination with the corresponding lake volume determined using a digital elevation model (DEM) designed by the authors.

The surface runoff (I_R) of the ambient lake slopes was derived from empirical findings (Dikau, 1986; Biemelt *et al*., 2005) describing the relationships between precipitation intensity, soil texture and moisture, inclination and vegetation. Because parameters like soil moisture and texture or inclination are highly variable, they generally yield rough estimates, especially when long evaluation periods are being assessed. Considering the field characteristics of ML Plessa 117, the surface runoff was estimated to be about 5% of the monthly precipitation. According to the DEM, the area that potentially drains into the lake (by inclination) is about 137 000 m^2.

RESULTS AND DISCUSSION

Surface water balance

The general hydrological water balance is described by Equation (1), which specifies all components that have to be considered:

$$\frac{dV}{dt} = P + I_R + I_{GW} + I_S - O_{GW} - O_S - E \qquad (1)$$

where $\mathrm{d}V/\mathrm{d}t$ is the temporal change in lake volume ($m^3\ yr^{-1}$), P the precipitation ($m^3\ yr^{-1}$, $mm\ yr^{-1}$), I_R the surface runoff from the lake slopes ($m^3\ yr^{-1}$), I_{GW} the groundwater inflow ($m^3\ yr^{-1}$), I_S the surface water inflow ($m^3\ yr^{-1}$), O_{GW} the groundwater outflow ($m^3\ yr^{-1}$), O_S the surface water outflow ($m^3\ yr^{-1}$) and E the evaporation from the lake surface ($m^3\ yr^{-1}$, $mm\ yr^{-1}$). The water balance components P and E were calculated using the monthly mean lake surface area in 2003, where I_R is related to the area of the accountable, ambient lake slopes (137 000 m^2).

In 2003, P, E, I_R, I_S, O_S and $\mathrm{d}V/\mathrm{d}t$ amounted to about 417 000 m^3, 636, 000 m^3, 3 020 m^3, 624 000 m^3, 1 325 000 m^3 and −142 000 m^3, respectively (Table II). The remaining unknown components in Equation (1) are I_{GW} and O_{GW}, which have an overall value of 774 000 $m^3\ yr^{-1}$. These components of the water balance equation could not be determined separately by this approach. Therefore, it was not possible to estimate the contribution of groundwater inflow to total annual input into the lake (ΔI_T) or the lake's mean residence time (τ). Determination of I_{GW} and O_{GW} required the use of a regional groundwater model (including ML Plessa 117) and the application of an isotope water balance using $\delta^{18}O$ for the catchment area of ML Plessa 117.

Estimation of groundwater inflow and outflow by the regional groundwater model

ML Plessa 117 and its catchment area are part of the regional groundwater model developed and described by Weber *et al*. (1998), Knoll *et al*. (1999) and Weber (2000); this model is based on MODFLOW, a modular three-dimensional finite difference groundwater model (McDonald and Harbaugh, 1988; Chiang and Kinzelbach, 1996). It consists of six layers representing the four quaternary and two tertiary aquifers or aquitards existing in the regional geological stratification. The grid has a dimension of 200 × 200 m and covers a total area of about 100 km^2, with ML Plessa 117 situated in the middle. The precipitation (P), evaporation (E) and groundwater recharge (I_{GWR}) were determined to be 560, 700 and 125 $mm\ yr^{-1}$. The model was calibrated to the groundwater contour, which was derived from the groundwater monitoring wells of the region (shown partially in Figure 1).

The water levels of all lakes and ditches of the model area lay slightly below the groundwater table. ML Plessa 117 and the other surface waters form local sinks that drain the surrounding groundwater (Weber, 2000; Figure 1). Consequently, the modelled O_{GW} of ML Plessa 117 was about zero. Since the groundwater flow of the region is directed from north to south, the groundwater catchment areas of the lakes are mainly located in the north. In the groundwater model, ML Plessa 117 has two distinct catchment areas that contribute groundwater fluxes to the lake. The major groundwater inflow comes from north-north-west and is about 716 000 $m^3\ yr^{-1}$. The minor inflow of about 95 000 $m^3\ yr^{-1}$ passes the tertiary dump site and enters the lake from west-south-west. The two fluxes amount to a total groundwater inflow (I_{GW}) of about 811 000 $m^3\ yr^{-1}$ (Table II). The calculated groundwater inflow contributes 42% of the total annual input (ΔI_T) into ML Plessa 117.

Since all water balance components are known, the lake mean residence time (τ) can be calculated using the equation:

$$\tau = \frac{V_m}{O_S + O_{GW}} \qquad (2)$$

where V_m is the mean lake volume, O_S the surface water outflow and O_{GW} the groundwater outflow. Based on the groundwater model data, ML Plessa 117 has a mean residence time (τ) of about 4·3 years (Table II).

Furthermore, the groundwater model revealed that the surface water inflow (I_S) from ML 118 into ML Plessa

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117 is fed totally by groundwater, which, in terms of quantity, is an important component of the water balance (Table II).

Due to the geologically heterogeneous stratification of the lake catchment area resulting from glacial excavation and erosion during the past ice ages (Nowel *et al.*, 1995), the accuracy of the applied groundwater model is limited. An additional source of uncertainty was the relative coarseness of the model grid compared with the catchment area of ML Plessa 117.

Estimation of groundwater inflow and outflow by $\delta^{18}O$ determination

Groundwater and surface water samples from the catchment area of ML Plessa 117 were taken so as to describe the origin of the water and to quantify the contribution of groundwater inflow and outflow (I_{GW} and O_{GW}) to the total water balance. The isotopic composition of the lake's surface water, the surface water inflow and the outflow from ML Plessa 117 and the surrounding groundwater are shown in Figure 2. Due to the different kinetic effects of $\delta^{18}O$ and $\delta^{2}H$ (Gonfiantini, 1986), waters influenced by vaporization move away from the Global Meteoric Water Line (GMWL), which is defined as $\delta^{2}H = 8\delta^{18}O + 10$. The characteristic Evaporation Line (EL) of the catchment area of ML Plessa 117 was found to be $\delta^{2}H = 5{\cdot}62\delta^{18}O - 13{\cdot}78$. This indicates that the catchment area reached steady-state conditions after the cessation of mining activities and after the filling of the pit and aquifers. The use of stable isotopes for water balance calculations is therefore permissible.

The $\delta^{18}O$ curves for lake surface water, surface water inflow and outflow and precipitation within a single year (2003) are shown in Figure 3. Since the water at the lake surface and the surface water outflow overlapped during the whole year, one can assume that the water samples taken at maximum depth are characteristic for the whole lake.

The absolute $\delta^{18}O$ values fluctuated only slightly (around $-5‰$). The lake surface water inflow from ML

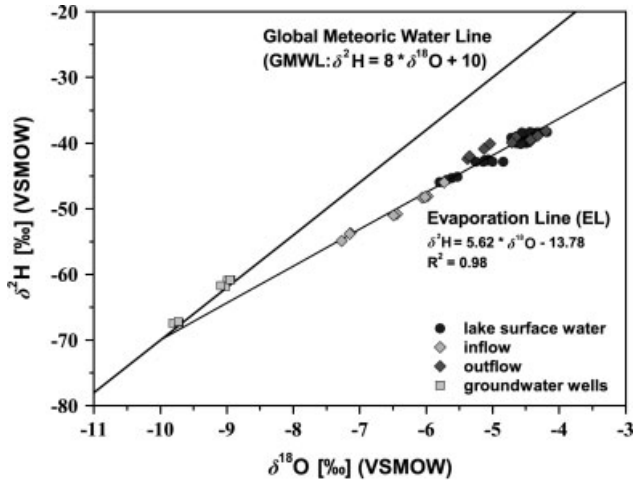

Figure 2. Proportion of $\delta^{18}O$ to $\delta^{2}H$ isotopes in different water bodies of the catchment area of ML Plessa 117

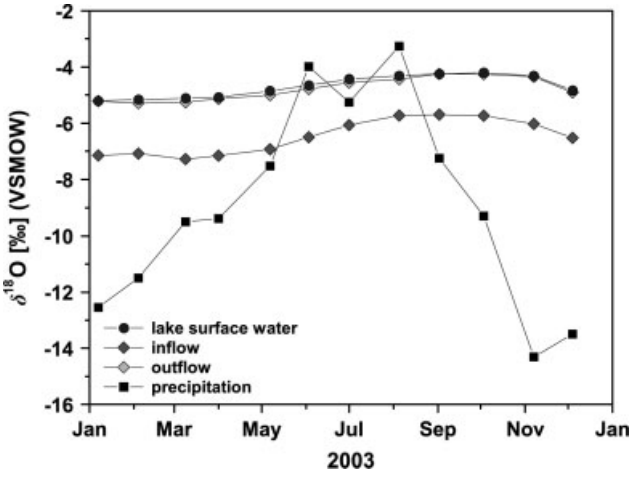

Figure 3. Temporal variation in $\delta^{18}O$ values of the lake water, surface water inflow and outflow (I_S and O_S), and precipitation (P) of ML Plessa 117 in 2003

118 followed the same seasonal pattern as the lake surface water, but the $\delta^{18}O$ values were much lower (-7 to $-6‰$). This indicated that the surface water of ML 118 contained more groundwater than the surface water of ML Plessa 117. Additionally, the surface water of ML 118 was exposed to evaporation for a shorter time because its residence time is shorter than that of the surface water of ML Plessa 117. The $\delta^{18}O$ values for precipitation fluctuated mostly between -14 and $-12‰$ in winter and -6 and $-3‰$ in summer.

Seasonal changes in the isotopic composition occurred near the surface, where $\delta^{18}O$ values increased from spring to autumn and decreased during winter due to reduced evaporation (Figures 3 and 4a). However, the fluctuations within the water column due to temperature stratification in summer and the formation of a well-mixed epilimnion and a separated hypolimnion were even more pronounced (Figure 4a and b). During the stratification period, the $\delta^{18}O$ values in the hypolimnion were significantly lower than those in the mixing period in winter. This is caused not only by the inhibition of evaporation of that part of the water body, but also by the accumulation of groundwater inflow (Figures 2 and 4a).

The hydrological water balance was calculated from the $\delta^{18}O$ values based on the isotope water balance equation:

$$\frac{dV}{dt}\delta^{18}O_L = (P + I_R)\delta^{18}O_P + I_{GW}\delta^{18}O_{GW} + I_S\delta^{18}O_{I_S} - (O_{GW} + O_S)\delta^{18}O_L - E\delta^{18}O_E \quad (3)$$

where $\delta^{18}O_L$, $\delta^{18}O_P$, $\delta^{18}O_{GW}$, $\delta^{18}O_{IS}$ and $\delta^{18}O_E$ stand for the oxygen isotopic composition of the lake water, the precipitation, the groundwater, the surface water inflow and the evaporate, respectively. The other variables are the components of the hydrological water balance outlined in Equation (1). When the monthly change in lake volume is known, the groundwater inflow can be

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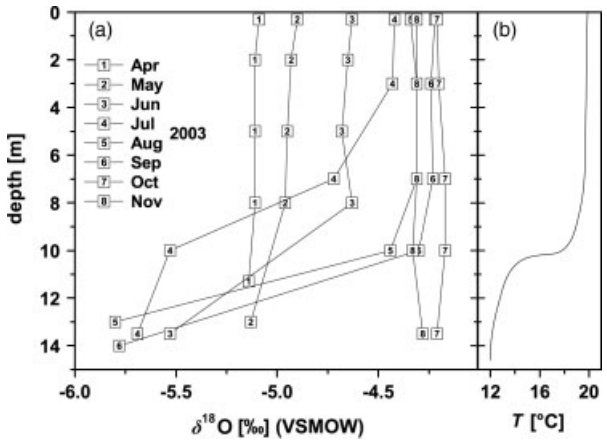

Figure 4. Temporal and spatial variation of δ^{18}O values in ML Plessa 117 depending on the lake stratification in 2003 (a). Temperature profile on 2 September 2003 (b). The profiles were taken at the point of maximum depth

derived by combining Equations (1) and (3):

$$I_{GW} = \frac{(P + I_R)\delta^{18}O_P + I_S\delta^{18}O_{IS} - E\delta^{18}O_E - (P + I_R + I_S - E)\delta^{18}O_L}{\delta^{18}O_L - \delta^{18}O_{GW}} \quad (4)$$

The isotope water balance and hence the groundwater inflow and outflow (I_{GW} and O_{GW}) were calculated using monthly meteorological, hydrological and isotope data collected during 2003 (Tables I and II). The air temperature (T_{air}), precipitation (P) and relative humidity (h) values were obtained from the Doberlug-Kirchhain weather station. The monthly evaporation flux from the lake surface area (E) was computed using LAKEoneD, an adapted one-dimensional stratification model. The overall E was about 674 mm yr^{-1}, corresponding to 636 000 m^3 yr^{-1}. The surface runoff (I_R) of the ambient lake slopes amounted to about 3 020 m^3 yr^{-1} and seemed to be of minor importance compared with other water balance components. The surface water inflow (I_S) and outflow (O_S), based on discharge measurements, amounted to about 624 000 m^3 yr^{-1} and 1 325 000 m^3 yr^{-1}, respectively. In 2003, the lake volume of ML Plessa 117 (dV/dt) decreased by about 142 000 m^3.

The average $\delta^{18}O_L$ value (−4·70‰) was calculated from the monthly sampling data in 2003 (Table I, Figure 3). The measured and averaged $\delta^{18}O_L$ values of the epilimnion were taken for the water balance calculation because the hypolimnic water body of ML

Table I. Isotope and meteorological data used to calculate the monthly $\delta^{18}O_E$ values and the isotope water balance

Month	T_{air} [°C] [1]	P [mm] [1]	E [mm] [cal.]	h [%] [1]	α (T) — [2]	$\delta^{18}O_P$ [‰] [3]	$\delta^{18}O_{IS}$ [‰] [3]	$\delta^{18}O_{IGW}$ [‰] [3]	$\delta^{18}O_L$ [‰] [3]	$\delta^{18}O_A$ [‰] [cal.]	$\delta^{18}O_E$ [‰] [cal.]
January	−1	63	5	90	1·01178	−12·55	−7·14	−8·95	−5·20	−24·26	35·36
February	−2	10	7	83	1·01197	−11·50	−7·08	−8·95	−5·15	−23·40	−0·35
March	4	30	14	80	1·01128	−9·50	−7·27	−8·95	−5·11	−20·72	−12·31
April	9	26	22	66	1·01085	−9·39	−7·15	−8·95	−5·07	−20·18	−21·57
May	16	22	72	69	1·01019	−7·52	−6·92	−8·95	−4·85	−17·66	−23·37
June	20	50	104	59	1·00982	−3·98	−6·49	−8·95	−4·65	−13·75	−29·77
July	20	65	110	71	1·00980	−5·25	−6·06	−8·95	−4·43	−15·00	−26·41
August	20	14	123	62	1·00976	−3·26	−5·72	−8·95	−4·31	−12·97	−30·11
September	15	33	90	74	1·01026	−7·24	−5·69	−8·95	−4·24	−17·45	−20·28
October	6	46	63	85	1·01110	−9·30	−5·73	−8·95	−4·20	−20·34	0·69
November	6	39	49	89	1·01107	−14·31	−6·02	−8·95	−4·31	−25·32	56·64
December	2	42	17	87	1·01151	−13·50	−6·52	−8·95	−4·83	−24·94	26·35
Weighted annual mean:						−9·05	−6·48	−8·95	−4·70		−15·44

Data taken from [1] DWD, [2] Majoube, 1971, [3] measured and [cal.] calculated.

Table II. Results and boundary conditions for the hydrological, geohydrological and isotope water balance calculations for the catchment area of ML Plessa 117

Water balance components		Units	Surface water balance	Groundwater model	Isotope water balance
Precipitation	P	[mm yr^{-1}]	441	560	441
Evaporation	E	[mm yr^{-1}]	674	700	674
Groundwater recharge	I_{GWR}	[mm yr^{-1}]	—	125	—
Surface runoff	I_R	[m^3 yr^{-1}]	3 020	—	3 020
Change in lake volume	dV/dt	[m^3 yr^{-1}]	−142 000	0	−142 000
Surface water inflow	I_S	[m^3 yr^{-1}]	624 000	600 000	624 000
Surface water outflow	O_S	[m^3 yr^{-1}]	1 325 000	1 300 000	1 325 000
Groundwater inflow	I_{GW}	[m^3 yr^{-1}]	774 000	811 000	914 000
Groundwater outflow	O_{GW}	[m^3 yr^{-1}]		0	140 000
Contribution of groundwater inflow to total annual lake input	ΔI_T	[%]	—	42	47
Mean residence time	τ	[yr]	—	4·3	3·9

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Plessa 117 was small (about 8% of the total lake volume) and more or less isolated during the stratification period (Figure 4). The average oxygen isotopic composition of the groundwater (−8·95‰) was calculated from the two sets of measured data obtained from four sampling wells located around the lake, which were not affected by lake water infiltration. Seasonal variations in isotopic composition were not observed (Table I). The $\delta^{18}O_P$ value, which was measured monthly at a sampling station on the western shore of ML Plessa 117, showed large evaporation-induced fluctuations during 2003 (Table I, Figure 3). The weighted (to the amount P per month) annual mean was −9·05‰.

Determination of $\delta^{18}O_E$ is related to major problems with the accuracy of sampling and measuring (Dincer, 1968; Zimmermann and Ehhalt, 1970; Allison *et al.*, 1979; Saxena, 1996). Since the variable could not be measured directly, it had to be calculated according to an equation derived from the resistance model of the evaporation process (Craig and Gordon, 1965):

$$\delta^{18}O_E = \frac{1}{1-h-\Delta\varepsilon}\left(\frac{\delta^{18}O_L-\alpha+1}{\alpha} - h\delta^{18}O_A - \Delta\varepsilon\right) \quad (5)$$

where $\delta^{18}O_A$ is the isotopic composition of the atmospheric vapour, h the relative humidity, α the equilibrium fractionation factor (R_{water}/R_{vapour} where R stands for $\delta^{18}O/\delta^{16}O$) and $\Delta\varepsilon$ the additional kinetic enrichment of ^{18}O during the evaporation of surface water bodies.

The annual mean of $\delta^{18}O_E$ was calculated as a weighted monthly $\delta^{18}O_E$ value depending on the seasonal variation of evaporation and precipitation (Yehdegho *et al.*, 1997; Knöller, 2000). The respective monthly $\delta^{18}O_A$ values were computed under inclusion of the equilibrium fractionation factor, the temperature and the isotopic composition of the precipitation. From the monthly data given in Table I, the weighted annual mean of $\delta^{18}O_E$ was determined to be −15·44‰.

The application of Equation (4) yielded an annual groundwater inflow (I_{GW}) of 914 000 m^3. By adapting Equation (1), the annual groundwater outflow (O_{GW}) was estimated to be 140 000 m^3. Since all water balance components are known, the mean residence time (τ) of ML Plessa 117, based on the results of the isotope water balance and derived from Equation (2), amounted to about 3·9 yr. Furthermore, the contribution of the groundwater inflow to the total annual input (ΔI_T) into ML Plessa 117 increased to 47% (Table II).

Sensitivity analysis. The isotope water balance of ML Plessa 117 in 2003 was calculated by combining the monthly averages of the meteorological parameters (P, E, h and T_{air}), the measured and estimated hydrological variables (I_S, O_S and I_R) and the isotopic composition of the lake. Since inter-annual changes can occur in all of these variables, the derived groundwater inflow and outflow (I_{GW} and O_{GW}) values are affected by these changes. To validate the results for later applications like matter and mass flux calculations, it is important to know their accuracy and sensitivity to various variables of the isotope water balance.

A sensitivity analysis was therefore conducted to show the changes in I_{GW} and O_{GW} depending on the variability of P, T_{air}, E, h, I_S, O_S, $\delta^{18}O_L$, $\delta^{18}O_P$, $\delta^{18}O_{IS}$, and $\delta^{18}O_{IGW}$. The changes in the meteorological and hydrological variables were selected on the basis of the double standard deviation of the long-term averages in previous

Table III. Variations of the groundwater inflow and outflow (I_{GW} and O_{GW}) resulting from changes in several components used for the isotope water balance calculations

		Variability of the parameter	Groundwater inflow (I_{GW}) [m^3]	Groundwater outflow (O_{GW}) [m^3]	ΔI_{GW} [m^3]	ΔO_{GW} [m^3]
Calculated value			914 000	140 000		
Precipitation	P	+50 [mm]	966 600	240 600	52 600	100 600
		−50 [mm]	861 400	39 400	−52 600	−100 600
Air temperature	T_{air}	+1 [K]	913 000	139 000	−1 000	−1 000
		−1 [K]	915 000	141 000	1 000	1 000
Evaporation	E	+10 [%]	1 074 500	237 000	160 500	97 000
		−10 [%]	753 500	43 000	−160 500	−97 000
Relative humidity	h	+2 [%]	547 000	−227 000	−367 000	−367 000
		−2 [%]	1 188 500	414 500	274 500	274 500
Surface water inflow	I_S	+10 [%]	887 800	176 300	−26 200	36 300
		−10 [%]	940 200	103 700	26 200	−36 300
Surface water outflow	O_S	+10 [%]	914 000	7 500	0	−132 500
		−10 [%]	914 000	272 500	0	132 500
$\delta^{18}O_L$		+0.2 [‰]	854 600	80 600	−59 400	−59 400
		−0.2 [‰]	979 200	205 200	65 200	65 200
$\delta^{18}O_P$		+0.2 [‰]	933 800	159 800	19 800	19 800
		−0.2 [‰]	894 200	120 200	−19 800	−19 800
$\delta^{18}O_{IS}$		+0.2 [‰]	943 400	169 400	29 400	29 400
		−0.2 [‰]	884 600	110 600	−29 400	−29 400
$\delta^{18}O_{IGW}$		+0.2 [‰]	959 100	185 100	45 100	45 100
		−0.2 [‰]	872 900	98 900	−41 100	−41 100

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years. The selected changes in the measured δ^{18}O values were consistent with the double analytical error of the respective analytical method (Knöller and Strauch, 2002). The single-variable responses are presented in Table III.

Most of the selected variables showed a moderate deviation from the calculated I_{GW} and O_{GW} values. Relative humidity (h), which appears to be a very critical variable, resulted in the highest changes of up to -260% for O_{GW}. This was already pointed out by Zimmermann and Ehhalt (1970) and Knöller (2000): the determination of $\delta^{18}O_E$ (Equation (5)) becomes very uncertain if the relative humidity approaches 80%. This effect is symbolized by the positive $\delta^{18}O_E$ values during the winter months (Table I).

CONCLUSIONS

This paper presents a method for quantification of groundwater inflow and outflow (I_{GW} and O_{GW}), which are the most important and most difficult to determine components of the water balance equation in the geologically very heterogeneously structured catchment area of ML Plessa 117. The isotope water balance was thereby compared with the surface water balance (which does not differentiate between I_{GW} and O_{GW}) and the local groundwater model. The groundwater model gave an I_{GW} of about 811 000 m^3 yr^{-1} and an O_{GW} of about zero, whereas the isotope water balance calculated fluxes of about 914 000 and 140 000 m^3 yr^{-1}, respectively (Table II).

Considering the mean residence time (τ) and the contribution of the groundwater inflow to the total annual input of the lake (ΔI_T), it could be shown that the groundwater model and the isotope water balance yielded comparable results despite the differences in I_{GW} and O_{GW} (Table II). Both the isotope water balance and the groundwater model are associated with several uncertainties, but less so in geologically very heterogeneous catchment areas in the case of the isotope water balance.

Like many other mining lakes of the region, the water balance of ML Plessa 117 is dominated by groundwater, which can have a decisive effect on the lake water chemistry, as manifested by the probable acid mine drainage from ambient dump sites.

The recalculated water balance could serve as the presupposition for matter and mass balances, for estimation of the effect of groundwater on the chemical composition of the lake water and, hence, for interaction between groundwater and surface water.

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