The net water budget of a lake without surface in- and outflow: a non-stationary approach

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ABSTRACT

The majority of the existing studies on the surface/groundwater balance in lakes assume stationarity of the groundwater flow at monthly or even annual scales. However, the groundwater exchange is closely connected to the water flows at the lake surface due to precipitation/evaporation, which are characterized by higher frequencies of temporal variability. Thus, the exchange between lake water and groundwater needs a non-stationary treatment. Whereas components of the water balance at the lake surface—the precipitation and the evaporation—can be estimated with reasonable accuracy from the standard meteorological observations, it is difficult to obtain the temporal variability of the groundwater flow in/out a lake from the field data on account of its high spatial heterogeneity. We present a method to estimate net groundwater input into the lake water budget as a rest term in the total water balance derived from high-resolution water level measurements by bottom-mounted pressure loggers. The method has demonstrated its reliability for estimation of the lake level variations on periods from sub-diurnal to perennial ones. The net groundwater flow revealed a pronounced seasonal component superimposed by perennial variations between wet and dry years, as well as by synoptic effects of lake water exfiltration into the groundwater aquifer following strong precipitation events. A strong relationship is derived between the groundwater flow and the water balance at the lake surface - the supposedly inherent feature of enclosed lakes with small watersheds.

KEYWORDS

Evaporation, groundwater flow, lake water budget, water level,

INTRODUCTION

In lakes without surface in- and outflow the groundwater flow is one of the most important components of water budget and external input of dissolved substances (Hood *et al.*, 2006; Nakayama and Watanabe, 2008). Both, experimental studies (Winter 1976; Lee *et al.*, 1980; Krabbenhoft and Anderson 1986; Cherkauer and Zager, 1989; Isiorho and Matisoff, 1990) as well as numerical modeling (Sacks *et al.*, 1992; Cheng and Anderson, 1993; Genereux and Bandopadhyay, 2001) were performed to study lake/groundwater interactions, often in combination with transport of solutes (Stephenson *et al.*, 1994; Sholkovitz *et al.*, 2003).

Most of the existing studies on the surface-groundwater balance in lakes assume a stady-state groundwater flow (Cheng and Andersson, 1994; Nützmann *et al.*, 2003). However, the groundwater exchange is driven by the time-dependent groundwater recharge and is closely connected to the water flows at the lake surface due to precipitation/evaporation, which are characterized by higher frequencies of temporal variability. The precipitation events are typically followed by the intensification or even changing of the direction of the net groundwater flow. This effect takes place on short daily or hourly time scales and remains out of scope of the methods with coarser time resolution. Hence, groundwater-surface water interactions are highly dynamic and a steady-state should not longer serve as a central, default assumption (Milly *et al.*, 2008). The exchange between lake water and groundwater varies with time and therefore needs a non-stationary treatment. Experimental techniques for the measurement of exchange between groundwater and lake water can only with difficulty be used for the total water budget (Nakayama and Watanabe, 2008). An alternative method for the evaluation of this budget could be the estimation of groundwater exchange as the residual in the balance between the water balance at the lake surface, in- and outflows, and lake volume (Pollman *et al.*, 1991). This method does not calculate the individual values of inflowing and outflowing components of groundwater, but provides valuable information on the net groundwater contribution to the water budget of the lake as an integral characteristic of the lake-groundwater interaction. Generally, changes in the groundwater recharge and the lake water level take place on temporal scales from synoptic (caused e.g. by local precipitation events) to seasonal (connected to variations in the groundwater recharge in the hydrologic year) to perennial ones (arising from variations in the annual sum precipitation-evaporation balance at the watershed). Thereby, the main temporal scales of this variability are determined by the regional climate, but the variability range is individual for every lake, depending on the watershed characteristics.

In this paper we estimate the groundwater climate of Lake Stechlin – a small enclosed lake without surface in- and outflows, located in north-eastern Germany. The estimation method consisted in determining of the net groundwater contribution into the lake water budget as a residual term in the total water balance derived from the known water level fluctuations in the lake. The water level fluctuations, in turn, were obtained from time-resolved pressure measurements at the lake bottom with sufficient accuracy and high temporal resolution. The dataset comprised two subsequent years 2006-2007, one characterized as “extremely dry” and another as “extremely wet” compared to the annual regional precipitation mean of 36 years. By this means, we were able to estimate the range of the groundwater flow variability on climatic scales that, complemented with the established seasonal and synoptic patterns, allowed us to reveal the typical features of groundwater interactions and to develop a simple relationship between them and the water balance on the lake surface.

METHODS

Study area

Lake Stechlin is situated in NE Germany (53^{o}10'N, 13^{o}02'E) about 100 km north of Berlin and has a surface area of 4.25 km^2 and an average volume of 96.88·10^6 m³ (Koschel and Adams, 2003). The lake is a deepest one in the Brandenburg region with maximum and the mean depths of 68.5 m and 22.8 m respectively. The water level of Lake Stechlin is regulated by ground water inflow, by precipitation and evaporation, and by temporal runoffs through the surrounding sand layers (Richter, 1997; Nützmann *et al.*, 2003). The 80% of the 12.57 km^2 lake watershed is covered by forest. The subsurface watershed is also rather small with the sharp rise of the groundwater table in the south–east and in the north–west directions. The summary discharge of in- and outflows is negligible (0.004 m^3s^{-1}).

To study the hydrologic budget of Lake Stechlin a stationary coupled water and chloride mass balance model has been developed before (Nützmann et al., 2003). A steady-state groundwater modeling study of Lake Stechlin watershed showed that with respect to different annual rainfall situations the subsurface flow regime is also changing (Holzbecher, 2001). According to this model, the groundwater flux G in Lake Stechlin is expected to reveal high temporal variability and to change its sign in the total water balance of the lake:

$$\frac{dV}{dt} = (p - e + g) * A, \tag{1}$$

where dV/dt [$m^3 s^{-1}$] is the rate of change of the lake volume; A [m^2] is the lake surface area, p and e [$m s^{-1}$] are is the precipitation rate and the evaporation rate, correspondingly. Here, the precipitation rate p refers to the water volume falling directly on the lake surface, where the inflow from the land surface assumed to be negligible.

Estimation of the water balance components

Lake volume variations. We have used pressure measurements at the bottom of Lake Stechlin in order to estimate directly the fluctuations of the water level and, consequently, of the lake volume dV/dt (Eq. 1). Data on the water level fluctuations were collected in two subsequent years, from 27 January to 20 September 2006 and from 29 March to 4 September 2007 by a pressure sensor (TDR-2050 RBR Canada, absolute accuracy 0.03 db, resolution < 0.0006 db) installed at 30m depth in the southern part of Lake Stechlin at few centimeters above the sediment, and sampling continuously with 10s record interval. The annual precipitation rates amounted in these years at 489 mm/year in 2006 and at 906 mm/year in 2007, which are representative for wet and dry years, correspondingly (the annual precipitation in 1958–1994 varied between 427 mm and 815 mm with the mean value of 658 mm (Richter, 1997)). Thus, among with the resolution of the less-than-seasonal time scales, the dataset provided the opportunity for comparison of the G variability in dry and wet conditions.

The time variations in the water level h_W were determined from the hydrostatic balance,

$$\rho g \frac{dh_W}{dt} = \frac{d}{dt}\left(p_W - p_{Atm}\right), \tag{2}$$

where p_W is the measured pressure at the lake bottom, p_{Atm} is the atmosphere pressure, and ρ is the freshwater density. Taking into account the steep morphometry of Lake Stechlin and small amplitudes of the level fluctuations h_W, the associated variations in the lake surface area A assumed to be negligible, and the volume variations were estimated simply as

$$\frac{dV}{dt} = A\frac{dh_W}{dt}, \tag{3}$$

with A taken as 4.25 km^2. Under this assumption, Eq. (1) reduces to

$$\frac{dh_w}{dt} = p - e + g, \tag{4}$$

and the lake water level at any moment t is given by

$$h_w(t) = h_w(t_0) + P - E + G, \tag{5}$$

where t_0 is the time of the observations start, and $P(t) = \int_{t_0}^{t} p(\tau)d\tau$, $E(t) = \int_{t_0}^{t} e(\tau)d\tau$, and $G(t) = \int_{t_0}^{t} g(\tau)d\tau$ – are the accumulated precipitation, evaporation and groundwater input correspondingly.

Precipitation-Evaporation balance p - e. Data on the precipitation rate *p* and meteorological characteristics necessary for estimation of the evaporation rate *e* were adopted from the standard weather observations at the near-shore station provided by the German Weather Service (DWD) for the period 1957-2003 and by the German Environmental Agency (UBA) for 2004-2007. The small area of the lake suggests negligible difference between the measured precipitation over the land surface and that over the lake that is also supported by Richter's (1997) estimations.

Evaporation rate *e* is, along with the lake-groundwater exchange, one of the most uncertain components of the water balance (4) owing to complex interactions at the air-lake boundary. Apart from direct evaporation measurements, which are rarely available and are difficult to interpret at the lake-wide scale, a number of widely-used approaches exist for estimation of *e*, ranging from simple bulk-formulae to coupled models of the atmospheric and lake boundary layers. The choice of an appropriate method for a certain lake depends usually on available observational data and characteristic regime of the air-lake interaction. In particular, such factors as the fetch-dependent roughness of the lake surface, strong stability of the lower atmospheric boundary layer over the colder lake surface in summer and typically very low wind speeds in small wind-shadowed lakes are among the problems resulting in the lack of a universal parameterization of *e* suitable for any lake. Richter (1997) had obtained monthly evaporation totals at Lake Stechlin in 1958-2001 using measurements by evaporation pans installed directly over the lake surface. This dataset, when coupled with the meteorological observations at the lake shore and with the surface temperature measurements, gave us the opportunity of comparing different methods for *e* calculation in order to choose the one with sufficient accuracy for Lake Stechlin conditions.

The evaporation measurements were compared with outputs from several empirical evaporation formulae recognized in the literature (Haltiner and Martin, 1957; Kazmann, 1965; Richards and Irbe, 1969; Orlob and Selna, 1970; Richter, 1997), all of the form:

$$E = C \cdot f(u) \cdot (e_s - e_a), \tag{6}$$

where $f(u)$ is a function of the wind speed u, measured at the height z_u above the lake level. e_s is the saturated water vapor pressure at water surface, e_a is the water vapor pressure at air temperature, C is an empirical coefficient.

The wind measurements at 10 m height from the near shore station were adjusted to z_u for each corresponding formula assuming the logarithmic wind profile within the surface boundary layer.

In addition to the 5 bulk evaporation formulae listed above, a more advanced scheme of the latent flux calculation was used, based on the model of the surface boundary layer of Zilitinkevich (1991) and implemented in the surface module of the lake temperature model FLake (Mironov *et al.*, 2010). In the scheme, the Monin-Obukhov similarity relations (see e.g. Yaglom, 1977) are used to compute turbulent fluxes of moisture. In case of strong stability in the surface air layer, when the gradient Richardson number exceeds its critical value and the Monin-Obukhov similarity relations yield zero fluxes, crude estimates of fluxes of momentum and of sensible and latent heat are obtained, assuming that the transport of momentum, heat and mass in the surface air layer is controlled by the molecular transfer mechanisms. A decision between turbulent and molecular fluxes and between fluxes in forced and free convection is made on the basis of flux magnitude.

The testing of the evaporation models was performed at the data from the period 1998-2001, for which daily water temperature measurements were available in addition to the standard meteorological observations.

RESULTS AND DISCUSSION

Evaporation estimates

In order to arrive at a reliable method for estimation of evaporation during the water level measurements in 2006-2007, we have compared the outcomes of several evaporation models against the monthly evaporation rates in 1998-2001 available from direct measurements with an evaporation pan installed on the lake surface (Richter, 1997). Generally, the data from the evaporation pan provide higher values than estimations given by all models tested (Fig. 1). This result can be referred, at least partially, to a known systematic overestimation of the true evaporation rate by the evaporation pan measurements (Winter, 1981; Eichinger, 2003). On the other hand all estimations given by non lake specific models yield similar values, which are several times lower than the measured evaporation rates, especially in summer (Fig. 1). The inconsistency is apparently conditioned by the specific features of the atmospheric boundary layer over the lake surface: a strong stability on account of the temperature difference between the summer air in summer and the cold surface of the deep lake, and low winds caused by the small lake area and the surrounding forest. Most of bulk-formulae are based on typical winds and stratification data over large open water bodies, particularly, over the ocean, and fail in these conditions. The Monin-Obukhov theory for the developed turbulent boundary layers underlying the FLake algorithm is also inapplicable for strongly stratified boundary layer (Cheng *et al.*, 2005). Still, the air-lake exchange of scalars, in particular, the water vapor, includes the transport by the intermittent turbulence in the strongly stratified air, and is essentially higher than that provided by the purely molecular exchange. In the absence of a theory adequately describing this exchange, the empirical formulae derived explicitly for such small and deep lakes are the most appropriate alternative for estimation of evaporation rates. The two formulae based on the small lake data are close to the pan measurements data, with the latter formula of Meyer (Kazmann, 1965) fitting slightly better to the data (RMS error 16.12 mm vs. 19.33 mm for the Richter (1997) formula). Therefore, the Meyer formula is adopted in the following for all estimations of the evaporation from the measured lake surface temperatures, and is coupled with the lake model FLake instead of its standard algorithm for calculation of the latent heat flux in the model scenarios.

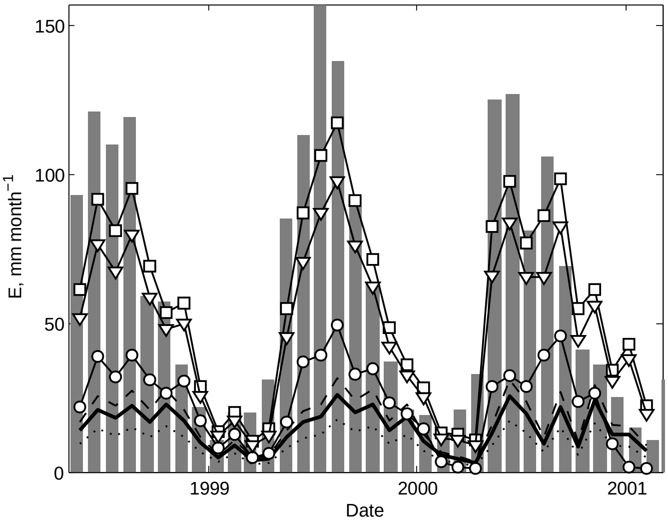

Figure 1. Monthly evaporation means from Lake Stechlin: evaporation pan measurements (gray bars) and those calculated after Richards and Irbe, 1969 (thick solid line), Orlob and Selna, 1970, dashed line), Haltiner and Martin, 1957 (dotted line); the Monin-Obukhov based Flake algorithm (Mironov *et al.*, 2010, line with circles), and the two lake-specific empirical formulae: Richter (1997, line with triangles) and Meyer (Kazmann, 1975, line with squares).

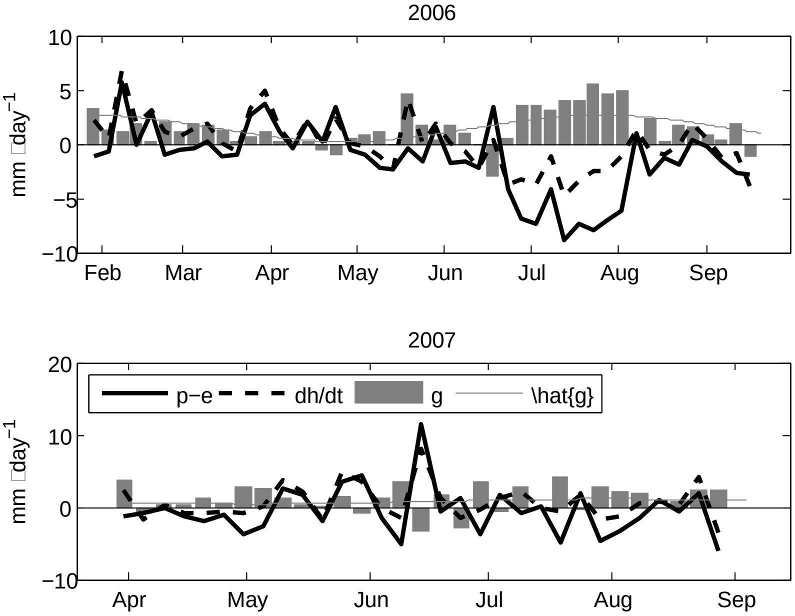

Figure 2. The water balance components in Lake Stechlin in (a) 2006 and (b) 2007. Thick solid line: precipitation-evaporation balance; dashed line: water level variability; gray bars: net groundwater inflow; thin gray line: approximation of groundwater inflow by Eq. (8).

Groundwater flow: short-term and seasonal fluctuations.

Qualitatively, the evolution of the lake level closely follows the cumulative precipitation-evaporation balance at the lake surface in 2006 as well as in 2007 (not shown). Among others, this fact demonstrates that the surface *P–E* balance determines, to a large degree, the short-term (days to months) variability of the water level in dry, as well as in wet conditions (Fig. 2). On the other hand, there is an additional positive component in the water balance in both years (the water level is higher that it would follow from the evaporation-precipitation balance only). In the absence of an appreciable permanent surface runoff, it is consistent to ascribe this discrepancy to the groundwater inflow. Approximating the accumulated groundwater inflow *G* by a linear fit, one arrives at a nearly constant groundwater contribution to the water level change at seasonal time scales of 1.45 mm/day in 2006 and 0.86 mm/day in 2007, which correspond to the net groundwater inflow of 6.17 10^3m^3/day and 3.67 10^3m^3/day, respectively. The residual variability in the groundwater inflow has remarkable differences between 2006 and 2007. In dry conditions of 2006 a pronounced seasonality persists in *G*, which is fairly well described by the sine function

$$\hat{G} = -A\sin\left(\frac{2\pi}{T}\left(t-T_0\right)\right) \text{ [mm]}, \tag{7}$$

or, correspondingly,

$$\hat{g} = -a\cos\left(\frac{2\pi}{T}\left(t-T_0\right)\right), \text{ [mm/day]}, \tag{8}$$

with the period T of 6 months, and the starting point T_0 set to 01 May (or 01 November) of the corresponding year. The seasonal amplitude amounts at $A = 35$ mm, or $a = 2\pi/T{*}A = 1.2$ mm/day. The same seasonal pattern is also present in 2007; is, however, much less expressed (the corresponding amplitudes are: $A = 10$ mm and $a = 0.35$ mm/day). In addition, the seasonal periodicity in the wet year 2007 is masked by short-term oscillations of *G*, which are closely linked to the precipitation events in a particular manner: relatively strong precipitation events are immediately followed by negative *g* and corresponding drop of *G* (cf. the precipitation and groundwater lines in Fig. 2b). Thus, the precipitation produces short events of *exfiltration* of the lake water into the aquifer. That is, apparently, a result of the lake-groundwater pressure gradient produced after strong rains, which do not affect immediately the groundwater level, but increase the hydrostatic pressure in the lake by raising its water level.

Generally, the results demonstrate a direct relationship between the groundwater flow *g* and the water balance at the lake surface ($p–e$): the higher evaporation in dry conditions is, i.e the larger negative ($p–e$) are, the stronger is the groundwater inflow; in turn, when precipitation prevails over evaporation ($p–e > 0$) the groundwater flow changes its sign to negative. Based on the data from both 2006 and 2007, this relationship fairly agrees with the direct proportionality $g = -0.6(p–e)$ (Fig. 3), i.e. the net groundwater exchange constitutes roughly 60% of the water balance at the lake surface and changes its sign according to it. The absolute data scatter around the approximating straight line is larger during exfiltration, when precipitation prevails over evaporation. This can be explained by higher non-stationarity of the water budget and by a certain role of the surface runoff during the precipitation events, which is not accounted for in Eq. 1. Still, for both positive and negative ($p–e$), the correlation between the approximation and the data is 0.65, or about 42% of the relative variability is explained by the proposed relationship. The largest scatter around the straight line is found in the vicinity of the zero point (empty circles in Fig. 3): excluding them from the correlation estimation increases the predictive ability of the relationship up to 60%. Adopting this dependence of *g* on the surface water balance, the variations of the lake water level in Lake Stechlin can be expressed from (1) in a simple way as:

$$\mathrm{d}h_W /\mathrm{d}t = 0.4(p–e). \qquad (9)$$

According to (9), the water level changes in the lake due to evaporative water losses and precipitation are damped to 60% by the lake-groundwater exchange, and the rest 40% should result in perennial water level variability (assumed the level is not artificially regulated).

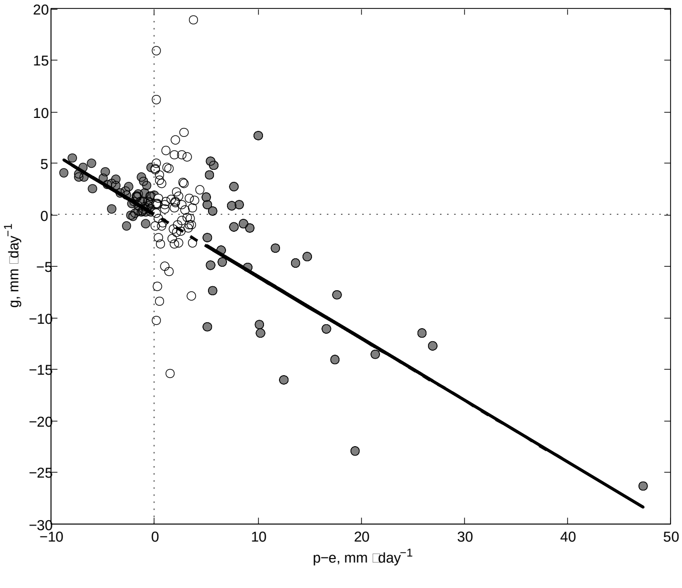

Figure 3. The net groundwater flow \$g\$ in both 2006 and 2007 plotted against the surface water balance (p-e) (circles). Open circles correspond to the weak precipitation events with 0<(p-e)<5 mm/day. The solid line corresponds to the ratio g = -0.6(p-e).

CONCLUSIONS

One aim of the present study was testing of the routine pressure measurements by standard-accuracy sensors as a tool for estimation of the lake level variations in a wide range of temporal scales. The analysis of the net water budget components in Lake Stechlin has demonstrated a close relationship between the water balance at the lake surface and the net groundwater flow in the lake. This relationship reveals itself at different time scales and produces distinct variations in the lake-groundwater exchange with periods from synoptic (driven e.g. by the strong precipitation events), to seasonal (connected to the mean groundwater level), to perennial ones (conditioned by the interannual differences in the regional precipitation-evaporation balance). The fact that these variations are to a large degree determined by the concurrent variations in the atmospheric drivers suggests that the pattern of the net groundwater flow variability in Lake Stechlin can be extrapolated, at least qualitatively, at the majority of enclosed lakes with small watershed:

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