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## Evaluation of three energy balance-based evaporation models for estimating monthly evaporation for five lakes using derived heat storage changes from a hysteresis model

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### Abstract

The heat storage changes ( $Q_t$ ) can be a significant component of the energy balance in lakes, and it is important to account for  $Q_t$  for reasonable estimation of evaporation at monthly and finer timescales if the energy balance-based evaporation models are used. However,  $Q_t$  has been often neglected in many studies due to the lack of required water temperature data. A simple hysteresis model ( $Q_t = a^*Rn + b + c^*dRn/dt$ ) has been demonstrated to reasonably estimate  $Q_t$  from the readily available net all wave radiation ( $Rn$ ) and three locally calibrated coefficients ( $a-c$ ) for lakes and reservoirs. As a follow-up study, we evaluated whether this hysteresis model could enable energy balance-based evaporation models to yield good evaporation estimates. The representative monthly evaporation data were compiled from published literature and used as ground-truth to evaluate three energy balance-based evaporation models for five lakes. The three models in different complexity are De Bruin-Keijman (DK), Penman, and a new model referred to as Duan-Bastiaanssen (DB). All three models require  $Q_t$  as input. Each model was run in three scenarios differing in the input  $Q_t$  (S1: measured  $Q_t$ ; S2: modelled  $Q_t$  from the hysteresis model; S3: neglecting  $Q_t$ ) to evaluate the impact of  $Q_t$  on the modelled evaporation. Evaluation showed that the modelled  $Q_t$  agreed well with measured counterparts for all five lakes. It was confirmed that the hysteresis model with locally calibrated coefficients can predict  $Q_t$  with good accuracy for the same lake. Using modelled  $Q_t$  as inputs all three evaporation models yielded comparably good monthly evaporation to those using measured  $Q_t$  as inputs and significantly better than those neglecting  $Q_t$  for the five lakes. The DK model requiring minimum data generally performed the best, followed by the Penman and DB model. This study demonstrated that once three coefficients are locally calibrated using historical data the simple hysteresis model can offer reasonable  $Q_t$  to force energy balance-based evaporation models to improve evaporation modelling at monthly timescales for conditions and long-term periods when measured  $Q_t$  are not available. We call on scientific community to further test and refine the hysteresis model in more lakes in different geographic locations and environments.

### 1. Introduction

Water stored in lakes and reservoirs is often the only source of water for downstream water users, including water for the domestic sector, industry, irrigation, wetlands and deltas. Evaporation is an important

component of the water and surface energy balance of lakes and reservoirs. Accurate quantification of evaporation is important for water resources management, lake water balance studies and prediction of the hydrological cycles in response to climate change (Finch 2001, Liu *et al* 2011, Xu and Singh, 2001).

**Table 1.** Summary of the lake characteristics, used monthly data and data sources for nine lakes. The first five lakes (No. 1–5) were used for testing evaporation modelling in this study. For the four lakes (No. 6–9), the available water surface temperature  $T_0$  and air temperature  $T_a$  were used together with other lakes for the development of the third evaporation model only, which is detailed in section 3.1. The meaning of notations in the column ‘Available data’ can be found in section 2.

No Lakes	Country	Latitude (°)	Elevation (m)	Mean depth (m)	Area (km <sup>2</sup> )	Data period	Available data	References
1	Vegoritisa <sup>a</sup> Greece	40.8	510	20	33.5	Feb. 1993–Jan. 1994	$Rn, Q_t, LE, T_a, T_0$	(Gianniou and Antonopoulos 2007)
2	Nojiri Japan	36.8	656	21	4.4	Jan.–Dec. 1966	$Rn, Q_t, LE, T_a, T_0, U$	(Yamamoto and Kondo 1968)
3	Mendota USA	43.1	259	12.8	39	1958–1959 Average	$Rn, Q_t, LE, T_a, T_0, RH$	(Dutton and Bryson 1962)
4	Ross Barnett USA	32.4	90	6	134	2008–2009	$Rn, Q_t, LE, T_a, T_0, RH, U$	Zhang and Liu (2013), Liu <i>et al</i> (2012)
5	Tahoe USA	39.1	1897	313	495	Sep. 2003–Aug. 2004	$Rn, Q_t, LE, T_a, T_0, RH, U$	Eddy covariance measurements are provided by Gayle Dana (Wartena 1959)
6	Kinneret Israel	32.8	–212	25.6	166	Mar. 1949–Feb. 1950	$T_a, T_0$	(Momii and Ito 2008)
7	Ikeda <sup>a</sup> Japan	31.2	65	125	10.6	1981–2005 Average	$T_a, T_0$	(Delclaux <i>et al</i> 2007)
8	Titicaca Peru-Bolivia	–15.5	3812	107	8372	1964–1978 Average	$T_a, T_0$	(Schertzer 1987)
9	Erie USA-Canada	42.2	173	19	25744	1967–1982 Average	$T_a, T_0$	

<sup>a</sup> The water surface temperature data were modelled values but were found in good agreements with measurements in their studies, thus we considered these data reliable and used in this study.

Many global hydrological models (Alcamo *et al* 2003, Oki and Kanae 2006, van Beek *et al* 2011) require accurate information on lake evaporation for water scarcity analyses and the prediction of ungauged river flows.

The eddy covariance (EC) technique is considered to be a reliable and accurate technique for direct measurements of evaporation from water bodies (e.g. Tanny *et al* 2008, Rimmer *et al* 2009). However, the EC technique is inappropriate for use on an operational scale due to the high instrument costs, and associated expensive technical expertise requirement (McJannet *et al* 2013). Therefore, direct EC measurements of evaporation are conducted for experimental research only and usually for a limited time period (Stannard and Rosenberry 1991, Assouline and Mahrer 1993, Blanken *et al* 2000, Allen and Tasumi 2005, Panin *et al* 2006, Blanken *et al* 2011). A summary of studies involving EC measurements for inland lakes is given in table 1 of Nordbo *et al* (2011). Despite the well-known imbalance issue for EC measurements that could affect the accuracy of evaporation, the EC technique is still generally considered to provide the most direct and least uncertain measurement of evaporation from lakes and reservoirs.

Since EC measurements are rarely available, indirect methods have to be used to estimate evaporation from lakes in most cases. Amongst various indirect methods, despite the inclusion of inaccuracies derived from each individual energy

components, the Bowen-ratio energy-budget (BREB) method is generally considered as being reliable and is often used as a reference against which other methods are compared (Assouline and Mahrer 1993, Brutsaert 1982, Elsawwaf *et al* 2010, Gianniou and Antonopoulos 2007, Rosenberry *et al* 2007, Sturrock *et al* 1992, Winter *et al* 1995, Winter *et al* 2003, Yao 2009). Several energy balance combination models (e.g. Penman, Priestley-Taylor, De Bruin-Keijman models) have also been widely used and reported good evaporation estimates for some lakes (Elsawwaf *et al* 2010, McJannet *et al* 2013, Rosenberry *et al* 2007, Winter *et al* 1995). The heat storage changes in the lakes can be a significant component of the energy balance (Finch 2001, Duan and Bastiaanssen 2015) particular for lakes where seasonal variation in water temperature is large, thus all the above mentioned methods require the determination of heat storage changes term (referred to as  $Q_t$  hereafter) for reasonable estimation of lake evaporation. Many studies have highlighted that  $Q_t$  is essential for accurate estimation of evaporation from lakes (Antonopoulos *et al* 2016, Finch 2001, Gallego-Elvira *et al* 2010). Incorporating  $Q_t$  will have a significant influence on the seasonal evaporation; it will significantly reduce evaporation during spring and summer and increase it substantially during the autumn and winter (Finch and Hall 2001).

The computation of  $Q_t$  requires detailed measurements of changes in vertical water temperature

profiles (Lenters *et al* 2005, Gianniou and Antonopoulos 2007, Momii and Ito 2008), that are rarely available for the vast majority of lakes around the world (Kirillin *et al* 2011). Therefore,  $Q_t$  has been considered as a prohibitively expensive variable when using the energy balance-based lake evaporation models (Rosenberry *et al* 2007). Although the difficulty in accounting for  $Q_t$  in lakes has been pointed out for decades, very little effort has been spent on the development of methods to estimate  $Q_t$  from easily available data. As a consequence, many studies had to simply neglect this important  $Q_t$  term in the energy balance-based models for estimating evaporation from lakes and reservoirs, which may make the estimated evaporation at monthly and shorter time scales suffer from large uncertainty.

Inspired by previous studies on the estimation of heat storage changes for soil (Camuffo and Bernardi 1982), urban (Grimmond and Oke 1999) and wetland surfaces (Souch *et al* 1996) rather than lakes, Duan and Bastiaanssen (2015) recently developed a simple empirical hysteresis model for estimating  $Q_t$  from net all wave radiation ( $R_n$ ) data for lakes at biweekly and monthly timescales, based on a comprehensive review and analysis of 22 lakes. The developed hysteresis model performed well and the estimated  $Q_t$  agreed reasonably well with local measured  $Q_t$  with the average coefficient of determination being  $R^2 = 0.83$  and the average root mean square error  $RMSE = 22 \text{ W m}^{-2}$  for a range of lakes and reservoirs with different characteristics. This simple hysteresis model thus provides a way to alleviate difficulties facing the preparation of  $Q_t$  as mentioned earlier and can be used as inputs to evaporation models.

As a follow-up study, the objective of this study is to answer the research question: what is the attainable accuracy of lake evaporation estimation using the estimated  $Q_t$  derived by the previously developed hysteresis model as inputs, when compared to the evaporation derived from BREB method or direct EC measurements? Three energy-based evaporation models were selected and compared for modelling lake evaporation. Five different lakes where reliable evaporation data either from BREB or EC measurements were obtained from published literature were used as testing sites for a more thorough analysis of the performance of evaporation models in different geographical settings. For each lake, all three evaporation models were performed using three scenarios with different  $Q_t$  as inputs to evaluate the impact of different  $Q_t$  inputs on the modelled evaporation.

## 2. Testing sites and datasets

After a search of published literature and other relevant data sources, five different lakes were selected

as testing sites for evaluation of modelled evaporation with different heat storage changes as inputs in this study. They were selected because of the availability of independent and reliable evaporation data from either the EC direct measurements or the BREB method which can be considered to be reliable and used as 'ground-truth' for evaluation purpose in this study following many previous studies (Winter *et al* 1995, Rosenberry *et al* 2007, Yao 2009, Elsawwaf *et al* 2010). The five lakes are, Lake Mendota, Lake Tahoe and Ross Barnett Reservoir in USA, Lake Nojiri in Japan, and Lake Vegoritisi in Greece. The characteristics of the five lakes, data periods and sources are presented in table 1. Four other lakes (Lakes Erie, Ikea, Kinneret and Titicaca) are also summarized in table 1, but for these lakes only air temperature and water surface temperature data were available and used only for the development of the third evaporation model as detailed in section 3.1 later. For the selected five lakes (No. 1–5 in table 1), the mean depth ranges from 6 m (Ross Barnett Reservoir) to 313 m (Lake Tahoe), and the surface area ranges from 4.4 km<sup>2</sup> (Lake Nojiri) to 495 km<sup>2</sup> (Lake Tahoe).

Lake Tahoe and Ross Barnett Reservoir had the evaporation data from direct EC measurements. For Lake Tahoe, the evaporation was measured through EC method by the Desert Research Institute, USA during September 2003–August 2004 and the data are not officially published. The measured annual total evaporation was 1154 mm, which is consistent with previous studies. For example Myrup *et al* (1979), who estimated the average annual evaporation of Lake Tahoe to be 1104 mm using water balance method with 38-month data from August 1967 to September 1970. Meijninger (2008) estimated the average annual evaporation over the period 2003 to 2004 for Lake Tahoe to be 1150 mm using the classical bulk approach. In addition, Huntington and McEvoy (2011) used the Complementary Relationship Lake Evaporation (CRLE) model, and reported the estimated average annual evaporation to be 1168 mm for Lake Tahoe from 2000 to 2009. For the remaining three lakes, the BREB method was used to compute the evaporation. All necessary data were extracted from the corresponding published literature for the five lakes (see table 1 for references).

Most available data from the published literature in table 1 were at monthly scale, and thus monthly data for all five lakes were compiled and the evaluation at monthly time scale was focused on in this study for the sake of consistency. All five lakes have data for only a complete year, except for Lake Mendota and Ross Barnett Reservoir. Lake Mendota had evaporation (latent heat flux) data for only nine months (Dutton and Bryson 1962). For Ross Barnett reservoir, data were available for two complete years (2008 and 2009). Ideally, the required data should include: net radiation ( $R_n$ ), heat storage changes ( $Q_t$ ), evaporation or latent heat flux (LE), air temperature ( $T_a$ ), water surface

temperature ( $T_0$ ), relative humidity (RH) and wind speed (U). However, the requirements were met for two lakes: Lake Tahoe and Ross Barnett Reservoir. For the other three lakes, data on wind speed and relative humidity were absent for Lake Vegoritis, data on wind speed was missing for Lake Mendota, and the data on relative humidity Lake Nojiri was missing. The data missing issue were because either they were unable to be extracted or not reported from the corresponding published literature. Such missing relative humidity and/or wind speed was filled using the ECMWF (European Center for Medium range Weather Forecasting) reanalysis products for the corresponding periods (<http://apps.ecmwf.int/datasets/>). The wind speed provided in the ECMWF reanalysis product refers to the value at the height of 10 m, and then the logarithm wind speed profile relationship (Allen *et al* 1998) was used to adjust that to the wind speed at the 2 m height for Lake Vegoritis and Lake Mendota.

It should be noted that the available measurements of heat storage changes  $Q_t$  involves two estimation methods. Ideally, the  $Q_t$  should be computed based on the water temperature profile data as detailed in e.g. Gianniou and Antonopoulos (2007) and Gallego-Elvira *et al* (2012). This requirement was met for all lakes except Lake Tahoe and Ross Barnett Reservoir. For both lakes, the water temperature profile data were not sufficiently available and thus  $Q_t$  was estimated as the residual of the energy balance ( $Q_t = Rn - H - \lambda E$ ). Clearly the residual  $Q_t$  would include all cumulative errors measured by the other energy balance components. The advective energy for Lake Tahoe was found to be negligible (Myrup *et al* 1979) and the Ross Barnett Reservoir can also be considered as negligible from the data presented by Liu *et al* (2012). As mentioned earlier in section 1, the measurements of water temperature profile for quantifying  $Q_t$  are not straightforward and many studies used the residual  $Q_t$  as representative in other lakes or reservoirs (Blanken *et al* 2000, Verburg and Antenucci 2010, Blanken *et al* 2011, Zhang and Liu 2013). Similar difficulties in quantifying the heat storage flux for wetlands was also reported by Souch *et al* (1996) who estimated the storage heat flux as the residual of energy balance and considered it as measured in their study. We acknowledge that the residual  $Q_t$  was not the ideal one, but such  $Q_t$  was practically 'best' available data for Lake Tahoe and Ross Barnett Reservoir. It is worth noting that the separately conducted studies by different authors might have different degrees of inaccuracies due to the non-uniform methods or instruments, but most published literature (table 1) where data were extracted from for use in this study did not provide any information about the uncertainty or error associated for each variable. Therefore, we assumed that the extracted data from the published literature were reliable, representative and practically best available for the

studied lakes. For the sake of simplicity and consistency, for all five lakes the available  $Q_t$  and evaporation data from sources listed in table 1 were referred to as 'measured' ones in this study. This is simply used to distinguish them from the modelled  $Q_t$  by the hysteresis model and modelled evaporation by three evaporation models in this study.

### 3. Methods

#### 3.1. Three selected evaporation models

Various methods for estimating evaporation from lakes have been tested before by for instance Winter *et al* (1995), Delclaux *et al* (2007), Rosenberry *et al* (2007), Yao (2009), Elsaywaf *et al* (2010). Based on their comprehensive comparisons, Priestley-Taylor (PT) (Priestley and Taylor 1972), Penman (Penman 1948), and the De Bruin-Keijman (DK) (De Bruin and Keijman 1979) models were generally found to generate reasonable and relatively accurate evaporation values. Recently, the Penman model was found to perform best for estimating evaporation from a shallow irrigation reservoir in Australia (McJannet *et al* 2013), although the authors referred to the used model as Penman-Monteith (Monteith 1965) in their paper. The characteristic big leaf resistance in the Penman-Monteith equation was ignored or set to zero, which implies that it is actually an alternative expression of the Penman equation. The DK model is actually a modification of the PT model based on net radiation and air temperature. Our initial analysis revealed that DK was performing better than PT for the tested five lakes. Hence, the DK and Penman models with different parameterizations were used in this study. The Penman model includes effects from air humidity, and thus follows a better physical theory than the DK model, see equations (1) and (2) for their equations:

$$\lambda E_{DK} = \frac{\Delta (R_n - Q_t)}{0.85\Delta + 0.63\gamma} \quad (1)$$

$$\lambda E_{Penman} = \frac{\Delta (R_n - Q_t)}{\Delta + \gamma} + \frac{c_p \rho_a (e_s - e_a) / r_a}{\Delta + \gamma} \quad (2)$$

where,  $\lambda E$  is the latent heat flux,  $Rn$  is the net all wave radiation, and  $Q_t$  is the heat storage changes, all three terms are in the unit of  $W m^{-2}$ ;  $\Delta$  is the slope of the saturated vapor pressure-temperature curve at air temperature ( $kPa \text{ } ^\circ C^{-1}$ );  $\gamma$  is the psychrometric constant ( $kPa \text{ } ^\circ C^{-1}$ ) that varies with the atmospheric pressure ( $P$ ,  $kPa$ ) that is a function of altitude (m) as described in equation (3),  $\lambda$  is the latent heat of vaporization ( $MJ \text{ } kg^{-1}$ );  $\rho_a$  is the density of air ( $kg \text{ } m^{-3}$ );  $c_p$  is the specific heat of air ( $MJ \text{ } kg^{-1} \text{ } ^\circ C^{-1}$ );  $e_s$  is the saturated vapor pressure at the air temperature ( $kPa$ );  $e_a$  is the vapor pressure at the air temperature ( $kPa$ ). The atmospheric pressure can be approximated

as (Allen *et al* 1998):

$$P = 101.3 \left( \frac{293 - 0.0065 \text{altitude}}{293} \right)^{5.26} \quad (3)$$

The Penman model requires an aerodynamic resistance  $r_a$  ( $\text{s m}^{-1}$ ) to be explicitly described, which can be calculated for open water bodies as (Chin 2011, Shuttleworth 2012):

$$r_a = \frac{4.72 \left( \ln \left( \frac{z_m}{z_0} \right) \right)^2}{(1 + 0.536 U z_m)} \quad (4)$$

where  $z_0$  is the roughness length (m), taken in this study as 0.00137 m (Chin 2011, Douglas *et al* 2009, Shuttleworth 2012).  $z_m$  is the height of wind speed measurements.  $U z_m$  is the wind speed  $U$  at  $z_m$  above the water surface ( $\text{m s}^{-1}$ ).

Further to the above two models, we also tested a simple energy balance residual method for estimating lake evaporation:

$$\lambda E = R_n - Q_t - H \quad (5)$$

where, the simple Ohm type of equation for computing the sensible heat flux  $H$  can be used (Kustas *et al* 1989, Liu *et al* 2007):

$$H = \frac{c_p \rho_a (T_0 - T_a)}{r_a} \quad (6)$$

where,  $T_0$  is the water surface temperature ( $^{\circ}\text{C}$ ),  $T_a$  is the air temperature ( $^{\circ}\text{C}$ ) and the aerodynamic resistance provided in equation (4) can be used again. Equation (6) requires the relationship between  $T_0$  and  $T_a$  to be known. In some cases this can be directly measured, but in other cases it needs to be approximated. Previous studies reported the strong linear relationships between  $T_0$  and  $T_a$  (Ali *et al* 2008, Gallego-Elvira *et al* 2010). In this study, we analyzed the relationship between  $T_0$  and  $T_a$  for all nine lakes where locally measured data on  $T_0$  and  $T_a$  were available (table 1), the results are summarized in table 2. Table 2 provides a further overview of experimental evidence of the strong linear relationships between  $T_0$  and  $T_a$  at monthly scale for nine different lakes from literature. This is an attractive condition that can be explored further for estimating various physical processes in lakes and reservoirs. As shown in table 2, the average slope and offset of the relationship  $T_0 = a^* T_a + b$  expressed in Celsius ( $^{\circ}\text{C}$ ) appears to be  $a = 0.83$  and  $b = 4.27^{\circ}\text{C}$ . After insertion of these coefficients in equation (6) and integration with equations (4) and (5), for a wind speed at the reference height of 2 m, it is feasible to compute the latent heat flux as:

$$\lambda E_{\text{DB}} = R_n - Q_t - \frac{c_p \rho_a (-0.17 T_a + 4.27) (1 + 0.536 U_2)}{251} \quad (7)$$

**Table 2.** The relationship between water surface temperature  $T_0$  ( $^{\circ}\text{C}$ ) and air temperature  $T_a$  ( $^{\circ}\text{C}$ ) for the nine different lakes at monthly timescale. Data are from literature listed in table 1.

No.	Lakes	$T_0 = a^* T_a + b$		
		$a$	$b$ ( $^{\circ}\text{C}$ )	$R^2$
1	Vegorititis	0.85	3.01	0.90
2	Nojiri	0.87	4.74	0.92
3	Mendota	0.88	3.31	0.94
4	Ross Barnett	1.04	1.62	0.99
5	Tahoe	0.78	4.58	0.96
6	Kinneret	0.67	8.47	0.94
7	Ikeda	0.92	3.19	0.94
8	Titicaca	0.47	9.16	0.65
9	Erie	0.98	0.38	0.99
	Average	0.83	4.27	0.91

Equation (7) has not been published before, and will be further referred to in this study as the Duan-Bastiaanssen (DB) model for lake evaporation. The DB model is included in this study because it has a parameterization that is different from the existing models for open water evaporation, and is therefore a new alternative with a strong physical basis that does not require the approximation of the saturated vapor pressure curve on the basis of air temperature measurements. The values of  $a = 0.83$  and  $b = 4.27^{\circ}\text{C}$  can be easily replaced with local values in case both  $T_0$  and  $T_a$  are measured. For all three evaporation models, the evaporation rate ( $\text{mm d}^{-1}$ ) can be obtained through dividing the computed latent heat flux ( $\text{W m}^{-2}$ ) by the latent heat of vaporization and the density of water.

As shown from equations (1), (2) and (7), the relative ranking of the three models in terms of increasing complexity and required data input is: DK, DB and Penman. Besides the common requirement of  $R_n$  and  $Q_t$ , the DK model requires air temperature only; the DB model requires wind speed as an additional input variable; the Penman model requires air temperature, wind speed and relative humidity. It should be noted that all three models involve empirical factors. The constants of 0.85 and 0.63 in the DK model are related empirical values because the DK model builds further on a relation between the empirically derived PT  $\alpha$ -coefficient and the Bowen ratio ( $H/\lambda E$ ). The empirical approximation of the Bowen ratio as specified by Hicks and Hess (1977) was used to derive the generic coefficients of the DK model as deduced in equation (1). Both Penman and DB models include the empirical solution of  $r_a$  (equation (3)), and DB has extra empirical coefficients ( $-0.17$  and  $4.27$ ) after accounting for the relationship between water surface temperature and air temperature.

Several studies reported that models can generate better evaporation estimates when the empirical coefficients were calibrated or optimized as site-specific constants (e.g. McJannet *et al* 2013). While

this is true in general, the only practical solution is to test the performance of the evaporation model with the default coefficients because data sets are rarely of sufficient quality to calibrate the coefficients for local lakes and reservoirs in most cases. Therefore, all three model with default coefficients shown in equations (1), (2) and (7) were tested in this study. The modelled evaporation values were then compared with measurements for five lakes.

### 3.2. The hysteresis model for estimating heat storage changes $Q_t$

The hysteresis model approximates  $Q_t$  from net all wave radiation  $Rn$  as:

$$Q_t = aRn + b + c \frac{dRn}{dt} \quad (8)$$

where,  $dRn/dt$  ( $W\ m^{-2}\ day^{-1}$ ) is the rate of the change (or time derivative) of  $Rn$ , and this term is used to account for the hysteresis-caused deviations from or deviations that could not be explained by the linear model ( $Q_t = a^*Rn + b$ ). The sinusoidal model similar to Gallego-Elvira *et al* (2010) provided the best fit to describe the behavior of  $Rn(t)$ . The value for  $dRn/dt$  was calculated by solving the analytical differentiation of the sinusoidal model  $Rn(t)$ . More details about the development of this hysteresis model can be found in Duan and Bastiaanssen (2015). Equation (8) requires three lake specific empirical coefficients ( $a$ ,  $b$ , and  $c$ ) to be known, and they can be locally calibrated for the period when measured  $Rn$  and  $Q_t$  are available. In this study, these three empirical coefficients were determined using the available  $Rn$  and  $Q_t$  measurements (through curve fitting) for each of the five investigated lakes. Once the three coefficients were determined,  $Q_t$  values were then estimated from  $Rn$  data using the equation (8) and were further compared with measured  $Q_t$  for evaluation. Two commonly used statistics  $R^2$  and RMSE were calculated for evaluation purpose. It should be noted that for four lakes where data were available for only one complete year (table 1), the measured  $Q_t$  were first used to calibrate three coefficients and then the same measured  $Q_t$  were further used to evaluate the estimated  $Q_t$  derived using the calibrated coefficients. Such evaluation could not be considered as completely independent, but it did offer a way to check to what extent the equation (8) with calibrated coefficients could reproduce the measured  $Q_t$ . Similar evaluation could be found in other studies as well (e.g. Souch *et al* 1996, Gianniou and Antonopoulos 2007). We hypothesized that once the three coefficients are locally calibrated for a lake then these coefficients can be used to predict  $Q_t$  for an independent period for the same lake. This hypothesis was tested for Ross Barnett Reservoir where measured data were available for two complete years 2008 and 2009. In this case,

the measured  $Rn$  and  $Q_t$  for the first year (2008) were used to derive the calibrated coefficients in equation (8) and then the calibrated coefficients together with measured  $Rn$  were used to predict  $Q_t$  for the year 2009. The predicted  $Q_t$  were then compared with measured  $Q_t$  for a completely independent evaluation of the predictive capability of the hysteresis model for the Ross Barnett Reservoir. If the hypothesis is confirmed, it means that the need for most troublesome  $Q_t$  can be somewhat eliminated by using an estimate  $Q_t$  from  $Rn$ . Thus the evaporation models simply require  $Rn$  and one or more of other meteorological variables ( $T_a$ , RH,  $U$ ) depending on the selected models.

### 3.3. Modelling evaporation with three different heat storage changes $Q_t$ as inputs

For each of the tested five lakes, all three selected evaporation models were run in three scenarios. The three scenarios differ only in using different  $Q_t$  as inputs to each evaporation model, which are described as follows:

Scenario 1: using measured  $Q_t$ .

Scenario 2: using modelled  $Q_t$  from the hysteresis model using  $Rn$  and locally calibrated coefficients.

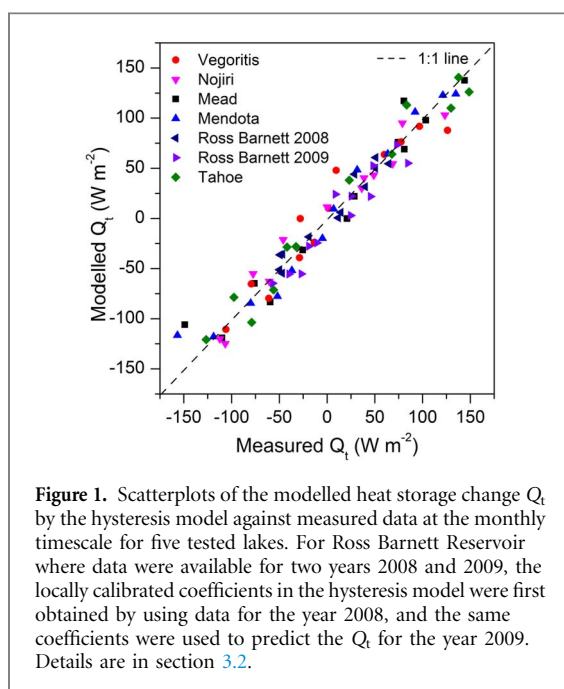
Scenario 3: using  $Q_t = 0$  which represents that the  $Q_t$  is neglected. Strictly speaking, the Scenario 3 should be avoided and it is expected to give the worst modelled evaporation, however, unfortunately the difficulties in accounting for  $Q_t$  mentioned earlier made this scenario occur in most practical hydrological studies (e.g. Vallet-Coulomb *et al* 2001, Wale *et al* 2009). This is why this scenario was kept in this study to show how large errors could be introduced in the modelled evaporation when the important  $Q_t$  is neglected.

For each scenario, the modelled evaporation values from three evaporation models were compared with the measured evaporation. The results of Scenario 1 will allow us to evaluate the performance of three evaporation models at their full potentials in the ideal case where the troublesome  $Q_t$  are available. Comparison of results among the three scenarios will enable us to evaluate the impact of  $Q_t$  on modelled evaporation and further evaluate the added value of the previously developed hysteresis model for estimating  $Q_t$  to the lake evaporation modelling.

## 4. Results and discussion

### 4.1. Evaluation of the hysteresis model for estimating heat storage changes $Q_t$

By fitting the measured  $Rn$  and  $Q_t$  data using the hysteresis model ( $Q_t = a^*Rn + b + c^*dRn/dt$ ), the lake-specific three coefficients ( $a$ ,  $b$  and  $c$ ) were determined for all five lakes at the monthly time scale, and such determined coefficients are referred to as locally calibrated ones. The performances of the fitted



hysteresis models were evaluated by comparing the modelled  $Q_t$  with the measured  $Q_t$  (figure 1), and a good agreement can be observed clearly. Table 3 summarizes the locally calibrated coefficients and performances of the hysteresis models for all five tested lakes. The three coefficients vary largely among lakes. Compared with measured  $Q_t$ , the modelled  $Q_t$  have an  $R^2$  larger than 0.92, and the RMSE ranges from 9.3 to 19.6  $W m^{-2}$ , indicating that the hysteresis model with locally calibrated coefficients is able to reproduce the measured  $Q_t$  at the monthly time scale for all five tested lakes. For Ross Barnett Reservoir, the result for the year 2009 represents the modelled  $Q_t$  using the locally calibrated coefficients derived using the data for the year 2008, which is thus a completely independent evaluation. As shown in figure 1 and table 3, the agreement between modelled  $Q_t$  and measured  $Q_t$  was fairly good ( $R^2 = 0.91$  and  $RMSE = 17.2 W m^{-2}$ ). This clearly confirms our hypothesis that once the three coefficients are locally calibrated for a lake then these coefficients can be used to predict  $Q_t$  for an independent period for the same lake. The modelled  $Q_t$  values were subsequently used as inputs to all three evaporation models for each individual lake, which represent the results of Scenario 2 for all five lakes (detailed in section 3.3).

#### 4.2. Evaluation of modelled evaporation using three different heat storage changes $Q_t$ as inputs

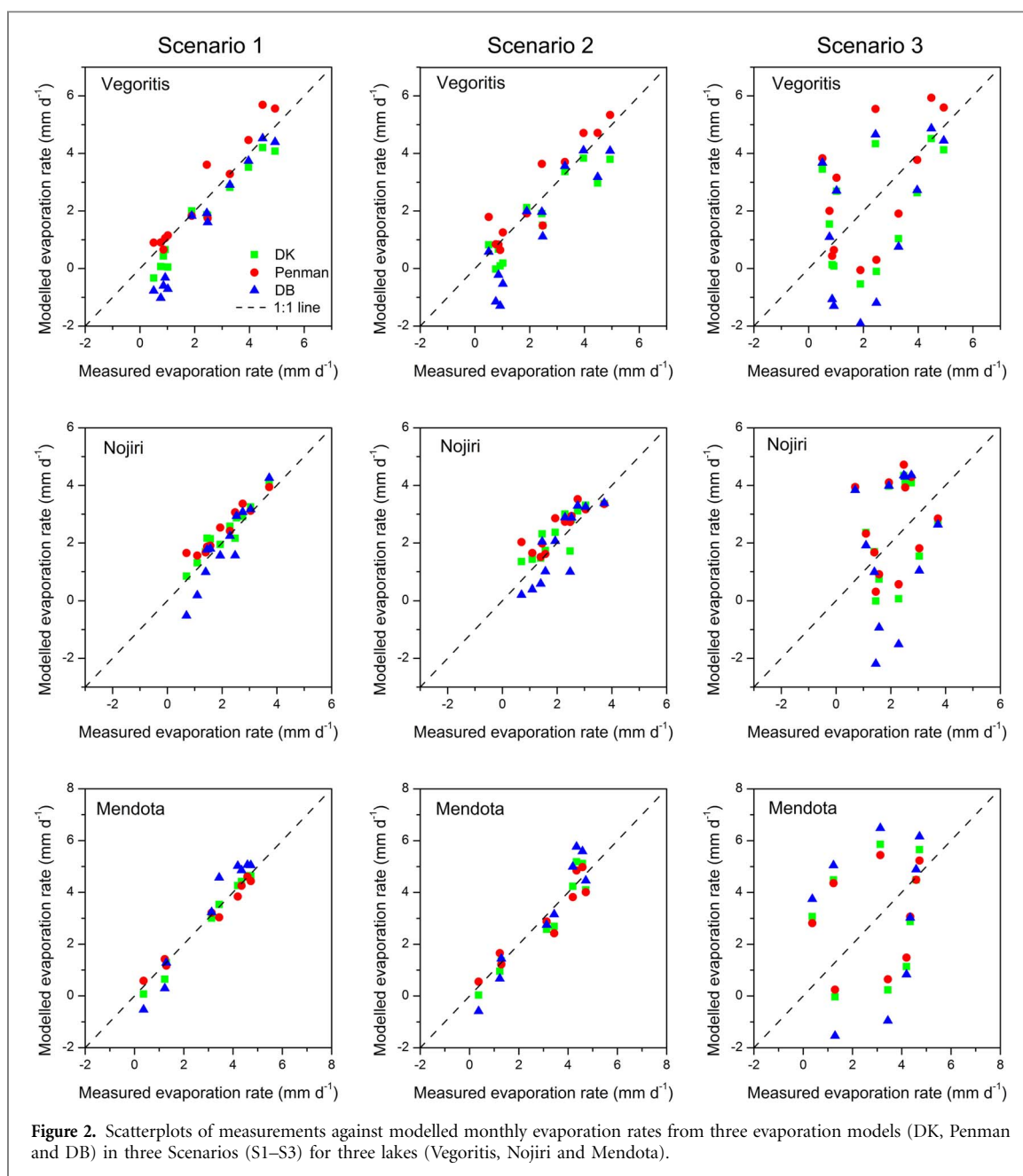
All three selected evaporation models were run in three scenarios with different heat storage changes  $Q_t$  as inputs for all five lakes. Comparisons between measured and modelled monthly evaporation rates for five lakes are presented in figures 2 and 3. The first impression from the figures is that the best agreements between modelled evaporation and measured were observed for the results of Scenario 1 (using measured

**Table 3.** Summary of locally calibrated coefficients of the hysteresis model for estimating heat storage changes  $Q_t$  from net radiation  $R_n$  and evaluation results for all five lakes at monthly time scale. For Ross Barnett Reservoir, the result for the year 2009 represents the modelled  $Q_t$  using the locally calibrated coefficients derived from the year 2008, thus providing an independent evaluation of the predictive capability of the hysteresis model.

No. Lakes	$Q_t = a^*R_n + b + c^*dR_n/dt$			Evaluation of modelled $Q_t$	
	$a$	$b$ ( $W m^{-2}$ )	$c$ (day)	$R^2$	RMSE ( $W m^{-2}$ )
1 Vegoritits	0.87	-52.58	45.66	0.92	19.6
2 Nojiri	1.36	-124.11	14.78	0.96	14.7
3 Mendota	0.81	-65.1	52.77	0.96	16.7
4 Tahoe	1.05	-120.6	24.86	0.97	17.1
5 Ross Barnett 2008	0.65	-66.55	19.01	0.95	9.3
6 Ross Barnett 2009				0.91	17.2

$Q_t$  as inputs) for all three evaporation models and for all five lakes while the worst agreements were observed for the Scenario 3 (neglecting  $Q_t$ ). Figures 2 and 3 clearly show that the results of Scenario 2 (using modelled  $Q_t$  as inputs) were very comparable to those of Scenario 1 and dramatically better than those of Scenario 3. The statistical indicators for performances of all three evaporation models for all five lakes and for all three scenarios are summarized in tables 4 and 5. For the results of Scenario 1, the modelled monthly evaporation rates by all three models compared reasonably well with the measured counterparts for all five lakes. The  $R^2$  ranged from 0.86 to 1.0. The RMSE ranged from 0.17  $mm d^{-1}$  for Ross Barnett Reservoir for the year 2008 by the DK model to 1.04  $mm d^{-1}$  for Lake Vegoritits by the DB model. By averaging the performance statistical values for all three models and for five lakes from tables 4 and 5, the average  $R^2$  was 0.96 and RMSE was 0.47  $mm d^{-1}$ . For the results of Scenario 3 with neglecting  $Q_t$ , all three evaporation models yielded very poor monthly evaporation estimates for all three models and for all five lakes with an average  $R^2$  of 0.30 and RMSE of 1.99  $mm d^{-1}$ , which stresses that the heat storage changes  $Q_t$  must be considered in the evaporation modelling for a reasonable estimation. For the results of Scenario 2, the average performance of all five lakes and three evaporation models had an  $R^2$  of 0.86 and RMSE of 0.64  $mm d^{-1}$ . In the Scenario 2, it is particularly worth noting that the results of the Ross Barnett Reservoir for the year 2009 represent a completely independent evaluation of the predictive capability of the hysteresis model because the used modelled  $Q_t$  were predicted using the hysteresis mode with locally calibrated coefficients derived by data in the year 2008. As clearly shown in figure 3 and table 5, using the predicted  $Q_t$  as inputs yielded reasonably good monthly evaporation estimates compared with measured counterparts and significantly better than results by neglecting  $Q_t$ . Taken together, we can conclude that the locally calibrated coefficients in the

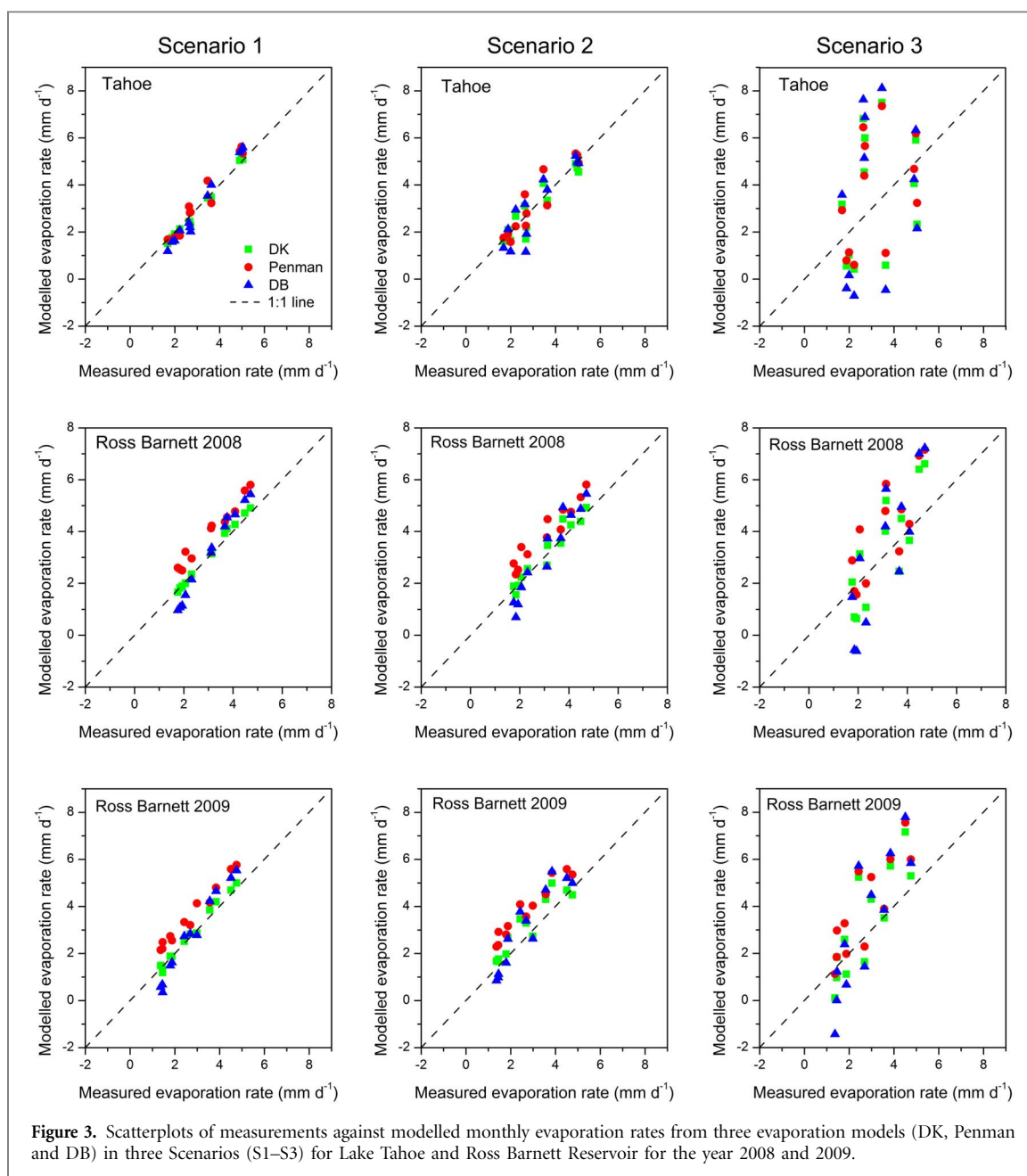




hysteresis model for  $Q_t$  using the historical data can be used to predict  $Q_t$  with good accuracy and further used to yield reasonably good modelled evaporation by all three evaporation models in the future for the same lake. This highlights the great potential of this simple hysteresis model to improve evaporation modelling for conditions when measured  $Q_t$  are not available (unfortunately this is true for the vast majority of lakes and reservoirs around the world) once locally calibrated coefficients can be determined.

It is worth discussing on several issues regarding the hysteresis model. The first issue is about the applicable time scales. Our previous study showed that the hysteresis model performed well at biweekly and monthly time scales (Duan and Bastiaanssen 2015). We found that the three calibrated coefficients ( $a$ ,  $b$  and  $c$ ) using monthly data showed very little differ-

ences from those determined at biweekly time scale for Lake Nasser that had complete data. This may suggest that the calibrated coefficients at monthly time scale could also be used to estimate biweekly  $Q_t$  values using corresponding  $R_n$  as input and to further force evaporation models for the same lake. However, this finding was based on only one lake and more validations are needed in different geographic locations and environments to test whether the calibrated coefficients will remain unchanged for various time scales. It should be noted that the biweekly time intervals is a commonly used time scale for water temperature profile measurements required for the calculation of  $Q_t$  (e.g. El Sawwaf and Willems 2012, Lenters *et al* 2005, Yao 2009), thus there is a need for measurements at finer time scales (e.g. weekly and daily) to further evaluate the applicable time scales



of our approach. A second issue is about the applicability of the hysteresis model to other lakes. For lakes that have no enough measured data to determine the locally calibrated coefficients, the empirical procedure proposed in our previous study could be used to estimate the three coefficients ( $a$ ,  $b$  and  $c$ ) from estimates of  $R_n$  and water surface temperature data, however, the estimated coefficients are expected to be less accurate than locally calibrated ones. We would like to call on scientific community to further test our hysteresis model if they have measured  $Q_t$  and  $R_n$  for more other lakes and to report the calibrated coefficients. Once we can obtain the local calibrated coefficients for a more sufficient range of lakes, it is possible to create a similar look-up table of typical coefficients for different lakes based on classification of lake characteristics and to develop a

better approach to estimate the coefficients. In addition, we admit that the number of lakes used for testing our approach was small due to the limited data availability. In future studies more efforts should be made to enlarge the dataset for improved understanding of heat storage changes in lakes and refining the applicability of our approach. In this regard, a similar network to FLUXNET (currently it is mainly for land surfaces) can be established to collect and share long-term measurements of water temperature profiles and energy flux specifically for a range of open water bodies in the world. Besides, actions can be taken to generate datasets for water temperature profiles and further heat storage changes for more lakes by exploring the potential of hydrodynamic models, e.g. the Flake model (Rooney and Jones 2010) and the DYRESM model (Weinberger and Vetter 2012).

**Table 4.** Comparison of measured evaporation and modelled evaporation from three evaporation models (DK, Penman and DB) in three scenarios (S1–S3) for three lakes (Vegoritits, Nojiri and Mendota).

Lakes	Scenarios	Methods	Total evaporation (mm)	Difference (%)	R <sup>2</sup>	RMSE (mm d <sup>-1</sup> )
Vegoritits	S1	Measured	841			
		DK	653	-22	0.97	0.60
		Penman	942	12	0.93	0.59
	S2	DB	528	-37	0.96	1.04
		DK	652	-22	0.86	0.75
		Penman	944	12	0.87	0.65
	S3	DB	526	-37	0.83	1.18
		DK	734	-13	0.21	1.75
		Penman	1011	20	0.32	1.83
Nojiri	S1	DB	589	-30	0.21	2.27
		Measured	761			
		DK	853	12	0.92	0.36
	S2	Penman	902	19	0.93	0.45
		DB	729	-4	0.85	0.55
		DK	854	12	0.74	0.50
	S3	Penman	903	19	0.75	0.58
		DB	727	-4	0.69	0.62
		DK	899	18	0.02	1.71
Mendota	S1	Penman	944	24	0.04	1.64
		DB	719	-6	0.03	2.24
		Measured	835			
	S2	DK	810	-3	0.99	0.23
		Penman	812	-3	0.99	0.23
		DB	877	5	0.96	0.69
	S3	DK	803	-4	0.92	0.52
		Penman	807	-3	0.90	0.51
		DB	859	3	0.93	0.75
	DK	849	2	0.04	2.35	
	Penman	849	2	0.06	2.09	
	DB	841	1	0.03	2.95	

It is also interesting to assess the relative ranking of three selected evaporation models in terms of their performance. To this end, only the results of Scenarios 1 and 2 were considered because it appears to be not meaningful to assess evaporation models for lakes and reservoirs without a solution for  $Q_t$  as showed by very poor results in the Scenario 3. The DK model generated the lowest RMSE values for three of the five lakes (Lake Nojiri, Lake Tahoe and Ross Barnett Reservoir) and for the remaining two lakes the RMSE by the DK model was nearly identical to the lowest values by the Penman model. For three out of the five lakes the  $R^2$  by the DK model was the highest, and for the remaining two lakes (Lake Nojiri and Lake Mendota) the  $R^2$  by the DK model was equal to or just very slightly smaller than those by the superior model. When considering all five lakes, the average performance values for the DK model were  $R^2 = 0.97$  and  $0.86$ , and  $RMSE = 0.29$  and  $0.53$  mm d<sup>-1</sup> in the Scenario 1–2, respectively. The average performance values for the Penman model were  $R^2 = 0.96$  and  $0.88$ , and  $RMSE = 0.53$  and  $0.66$  mm d<sup>-1</sup> in the Scenario 1 and 2, respectively, while for the DB model were  $R^2 = 0.95$  and  $0.84$ , and  $RMSE = 0.62$ ,  $0.75$  mm d<sup>-1</sup> in

the Scenario 1 and 2, respectively. This suggests that the DK model requiring minimum input data can be generally considered as the preferred prediction model in estimating of monthly evaporation rates. We admit that for three lakes (Vegoritits, Nojiri and Mendota) the results of modelled evaporation for the Penman and DB model might include the additional uncertainty due to the missing wind speed and/or humidity from the corresponding data sources were filled by a different data source in this study, which might affect the performance of the Penman and DB model to some extent. However, using results for only Lake Tahoe and Ross Barnett Reservoir without missing data issue still show that DK model is the best performing model. It is worth mentioning that the DK model has also been recognized as the best or second-to-best performing model for Williams Lake in USA (Winter *et al* 1995), Mirror Lake in USA (Rosenberry *et al* 2007), Dickie Lake in Canada (Yao 2009) and Lake Nasser in Egypt (Elsawwaf *et al* 2010). Hence, it does not seem to be a coincidence that the DK model came out as being a favorable evaporation prediction method in this study. Besides the commonly required  $Rn$  and  $Q_t$  among three models, the DK model only

**Table 5.** Comparison of measured evaporation and modelled evaporation from three evaporation models (DK, Penman and DB) in three scenarios (S1–S3) for Lake Tahoe and Ross Barnett Reservoir for the year 2008 and 2009.

Lakes	Scenarios	Methods	Total evaporation (mm)	Difference (%)	$R^2$	RMSE (mm d <sup>-1</sup> )
Tahoe	S1	Measured	1154			
		DK	1121	−3	0.99	0.19
		Penman	1167	1	0.96	0.33
	S2	DB	1176	2	0.98	0.40
		DK	1118	−3	0.86	0.46
		Penman	1165	1	0.87	0.47
	S3	DB	1174	2	0.80	0.65
		DK	1313	14	0.07	2.49
		Penman	1321	14	0.15	2.16
Ross Barnett 2008	S1	DB	1349	17	0.06	3.11
		Measured	1125			
		DK	1158	3	1.00	0.17
	S2	Penman	1373	22	0.98	0.70
		DB	1145	2	0.99	0.49
		DK	1157	3	0.94	0.30
	S3	Penman	1372	22	0.93	0.73
		DB	1143	2	0.93	0.54
		DK	1234	10	0.69	1.30
Ross Barnett 2009	S1	Penman	1437	28	0.66	1.42
		DB	1197	6	0.71	1.71
		Measured	996			
	S2	DK	1032	4	0.99	0.19
		Penman	1248	25	0.98	0.71
		DB	997	0	0.98	0.52
	S3	DK	1150	15	0.87	0.61
		Penman	1339	34	0.93	0.99
		DB	1139	14	0.85	0.75
		DK	1203	21	0.72	1.44
		Penman	1386	39	0.71	1.56
		DB	1163	17	0.73	1.82

requires air temperature data, and is therefore less vulnerable to the quality of other input wind speed and relatively humidity conditions of the lower part of the atmospheric boundary layer over water surfaces. The requirement for more input variables can be an obstacle for applying the Penman model to certain cases from practical perspectives. In addition, although the average performance of all five lakes showed that the DB model was the worst performing model, it is interesting to note that for Ross Barnett Reservoir the DB model performed better than the Penman model in terms of both  $R^2$  and RMSE values (table 5). It is therefore recommended to also include the DB model in future comparison studies of lake evaporation. The Penman model, used widely in regional and global scale hydrological studies, should be evaluated more critically.

As far as the annual total evaporation values are concerned, for the DK model the percentage difference from measurements ranged from −22% to 12% with the average absolute value of 8% for the Scenario 1 and 2 for the five lakes. The Penman model differed from the total evaporation by ranging between −3% to 34% with an average absolute value of 14%. The percentage difference for the DB model ranged from −37% to

17%, with an average absolute value of 9%. For the results in Scenario 3 by neglecting  $Q_t$ , the estimated annual total evaporation values were close to those in the Scenario 1 and 2, the average absolute percentage difference from measurements was 12%, 21% and 11% for the DK, Penman and DB models, respectively. This is expected because the heat storage changes  $Q_t$  would be small and ideally close to zero on the annual scale. The generally accepted errors for direct latent heat flux measurement from eddy covariance are in the range of 10 to 20%; so basically all three evaporation models could be regarded as acceptable.

## 5. Conclusions

As a follow-up study of the previously developed hysteresis model ( $Q = a^*Rn + b + c^*dRn/dt$ ) for estimating the heat storage changes ( $Q_t$ ) for lakes and reservoirs using the readily available net all wave radiation ( $Rn$ ), this study evaluated whether the derived  $Q_t$  from this hysteresis model could enable energy balance-based evaporation models to yield good evaporation estimates. To this end, three energy balance-based evaporation models were evaluated for

five different lakes at the monthly timescale where reliable reference evaporation from either the Bowen Ratio Energy Budget (BREB) or direct Eddy Covariance (EC) measuring methods were obtained from published literature. The three evaporation models are the De Bruin-Keijman (DK), Penman and Duan-Bastiaanssen (DB) models. The DB model is a new energy balance residual model based on an Ohm-type parameterization of sensible heat flux with standard coefficients, and launched in this paper. A general linear relationship between water surface temperature and air temperature from experimental data from nine lakes is the basis for the DB model. All three models require the heat storage changes ( $Q_t$ ) as input.

Evaluation results showed that the simple hysteresis model performed well in estimating  $Q_t$  for all five lakes at the monthly timescale. Independent evaluation further confirmed that this hysteresis model can be used to predict  $Q_t$  with good accuracy once locally calibrated coefficients ( $a-c$ ) are determined using the historical data. Using the estimated or predicted  $Q_t$  as inputs, all three evaporation models resulted in reasonably well evaporation estimates for all five lakes, and the modelled monthly evaporation were comparable to those using measured  $Q_t$  as inputs and significantly better than those with  $Q_t$  neglected. Considering that  $Q_t$  can rarely be derived from operational measurements for the major vast majority of lakes and reservoirs around the world, once three coefficients are locally calibrated using historical data, the simple hysteresis model offers a practical way of computing  $Q_t$  and it can be further used to improve evaporation modelling at the monthly timescale for conditions and long-term periods when measured  $Q_t$  are not available. We admit that the number of lakes used for testing our approach in this study was small due to the limited data availability, but the rationale for our study was driven by this limitation. We call on testing our approach in more lakes in different geographic locations and environments and at higher time scales (e.g. weekly and daily) once required data are available in the future. More efforts should be made in the measuring and modelling community to enlarge datasets for water temperature profiles and energy flux for more lakes in the world. Such datasets would facilitate a more comprehensive evaluation and development of existing and new methods for heat storage changes and evaporation from lakes.

All three evaporation models could be regarded as acceptable in estimating annual total evaporation. The DK model, requiring minimum input data can be generally considered as the best performing evaporation model in estimating monthly evaporation rates. For one lake, the new DB ranked second followed by the classical Penman model. The DB model requires more testing, although the first model tests are encouraging. The widely used Penman model should be evaluated more critically.

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