INFLUENCE OF GROUNDWATER INFLOW ON WATER TEMPERATURE SIMULATIONS OF LAKE AMMERSEE USING A ONE-DIMENSIONAL HYDRODYNAMIC LAKE MODEL

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With 5 figures and 1 table
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Summary: In this study we implemented groundwater inflow to the one-dimensional hydrodynamic simulation of lake water temperatures to improve the reproduction of the real water temperatures by the simulation results for Lake Ammersee, Southern Germany. As the hydro-geological conditions at Lake Ammersee have not yet been finally clarified, we created simulation scenarios for the hydrodynamic modeling with various characteristics of sub-terrestrial inflow. The scenarios were based on a review of the state of available information regarding the geology of the Ammersee basin. Analysis of the simulation results for each scenario revealed obvious alterations in the reproduction of real-temperature in comparison to those produced without accounting for subsurface inflows. For some inflow characteristics the implementation of groundwater inflow induced more accurate approximations of simulation results to real conditions for almost all depths and seasons. This implies that the hydrodynamic simulation of water temperatures at Lake Ammersee, including subsurface inflow, provides reliable results. Additionally it was possible to estimate roughly the potential conditions of groundwater inflow into the lake.

Zusammenfassung: In dieser Studie wurden Grundwasserzuströme bei der Modellierung der Wassertemperaturen des Ammersees (Süddeutschland) unter Verwendung eines eindimensionalen Wärmehaushaltsmodells berücksichtigt, um die Abbildung der realen Wassertemperaturen durch die Simulation zu verbessern. Da die hydrogeologischen Begebenheiten um den Ammersee noch nicht abschließend erforscht sind, wurden Szenarien mit verschiedenen Eigenschaften der unterirdischen Zuflüsse für die hydrodynamische Modellierung erstellt. Diese Szenarien basierten auf der Auswertung zu den verfügbaren Informationen über die Geologie des Ammerseebeckens. Im Vergleich zu den Simulationsergebnissen, welche nur oberirdische Zuflüsse berücksichtigten, ergaben sich für jedes Szenario deutliche Veränderungen in der Abbildung der realen Wassertemperaturverhältnisse. Die Studie zeigt, welche Ausprägungen der Grundwasserzuströme eine bessere Annäherung der Simulationsergebnisse an die realen Verhältnisse bewirkt. Daraus lässt sich folgern, dass die Wärmehaushaltsmodellierung am Ammersee durch die Berücksichtigung von unterirdischen Zuflüssen belastbare Ergebnisse erzielt und gleichzeitig eine grobe Abschätzung der potentiellen Verhältnisse der Grundwasserzuströme erfolgen kann.

Keywords: Lake Ammersee, hydro geology, hydrodynamic modeling, lake water temperatures, ground water

1 Introduction

As lakes can be considered to be sentinels of climate change (Adrian et al. 2009; Williamson et al. 2009), the simulation of future water temperatures using hydrodynamic models enables the evaluation of impact of changing climatic conditions on lakes. In order to carry out such simulations at Lake Ammersee, Southern Germany, the one-dimensional hydrodynamic lake model DYRESM (Dynamic Reservoir Simulation Model) was successfully calibrated for the site (Bueche and Vetter 2014). As applied in previous modeling studies of Lake Ammersee, e. g. by Joehnk and Umlauf (2001) or Danis et al. (2003), as well as in applications of DYRESM on natural lakes elsewhere, e. g. Gal et al. (2003), Tanentzap et al. (2007), Rinke et al. (2010) or Bayer et al. (2013), only surface inflows were considered. Lake-groundwater interactions have already been included in other hydrological studies, such as the simulation of catchment and lake water balances (Legesse et al. 2004; Niedda and Pirastru 2013) and the investigation of lake-stream networks (Woo and Mielko 2007). The conditions of the subsurface inflow to the lakes were either measured or assumed by previous studies (groundwater level, salinity, or inflow amount), but were not implemented in a hydrodynamic lake model, such as DYRESM, to simulate the influence on the water temperatures.

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It is to be assumed that the inclusion of groundwater inflow in DYRESM would have an impact on the simulation of the lake's water temperatures and heat budget. In order to achieve an improvement in the reproduction of real water temperature conditions compared to the simulation without groundwater inflows, in this study we implement subsurface inflow(s) to the input data of the lake model. So this is the first study simulating the heat budget of Lake Ammersee in consideration of potential subsurface inflows.

Investigations about the hydro-geological dynamics at Lake Ammersee which would enable the derivation of the subsurface inflow characteristics do not exist and measurement data are very rare for the entire wider lake environment and therefore are not representative. Hence scenarios of the characteristics of subsurface inflow are created based on a review of the available information regarding the hydro-geology of the Lake Ammersee basin and then adapted iteratively to improve the simulation results. Using scenarios instead of conduct field measurements enables an expeditious execution of this investigation. As a result of this modeling approach, the subsurface scenario characteristics, which induce the best approximation of the simulated to the real water temperatures, will help to receive a more detailed idea of the local hydro-geological conditions.

In sum, in the present study we want: (i) to show, that DYRESM provides reliable simulation results for the water temperatures of Lake Ammersee by the implementation of groundwater inflow, and (ii) to improve the reproduction of the real lake water temperature conditions in contrast to the simulations considering only surface inflows. In addition, this modeling approach allows a rough estimation of the characteristics of the inflows entering the lake sub-terrestrially.

2 Study site

Located 35 km south-west of Munich, in Southern Germany (47°59'N, 11°7'E) (see Fig. 1), the Lake Ammersee basin is glacial-morphological in origin and is considered to be typical of most pre-alpine lakes both locally and across the eastern part of the northern Alpine Foothills (Danis et al. 2004; Vetter and Sousa 2012). With a volume of 1.8 x 10^9 km³, a surface area of 46.6 km², a maximum depth of 83.7 m, and an average depth of 38.6 m the lake can be characterized as medium-sized. Lake Ammersee currently has a dimictic mixing regime. The occurrence of complete ice cover during winter is rare, last occurring in 2006 (Bueche and Vetter in revision). Under natural conditions the lake is potentially oligotrophic (Kucklentz 2001). After a period of eutrophism, especially before 1980, a process of reoligotrophication has set in as a result of water management activities which have led to an improvement in the lake's current trophic condition (Lenhart 1987; Vetter and Sousa 2012).

The residence time of the lake water is estimated to be around 2.7 years (Lenhart 1987; Dokulil et al. 2006), with the total catchment area covering 993 km² (Schaumburg 1996). The lake is drained by the Amper River in the north (long-term mean discharge: 21.1 ms^{-1}), the main tributary is the Ammer River entering from the south, which contributes about 80% of total annual lake runoff (long-term mean discharge: 16.6 ms^{-1}).

The whole tongue-shaped basin of Lake Ammersee was shaped into Tertiary and Quaternary sediments by the lobe of the Isar-Loisach-glacier (Alefs et al. 1996), which left the Alps to in the north during the Pleistocene. The resulting Tertiary surface has been investigated particularly, with the south mapped by Jerz (1993) and the eastern basin by Krause (2001) (see Fig. 2). After Wolf (2006), the pre-quaternary underground of the Ammer watershed can be considered as an aquiclude of sub-surface waters; however, the isohypses of the tertiary sediments indicate that the deepest point of the lake (449.3 m a.s.l.) lies above the tertiary rocks. The edges of the basin to the sides and to the north are built by late moraines (Würm) characterized by poor water permeability (Wolf 2006). In contrast, the southern part of the basin has been filled since the end of the last glacial by Holocene material including lake beds, alluvial and floodplain sediments of the Ammer River (Czymzik et al. 2010), and turf. The above-described hydro-geological conditions suggest that groundwater inflow largely enters Lake Ammersee from the south, with minor input from the east.

3 Methodology

3.1 Model description

In the present study, the one-dimensional hydrodynamic model DYRESM (v4.0.0-b2) was used to simulate the vertical distribution of lake water temperatures. The numerical model was developed by the Centre of Water Research (CWR) at

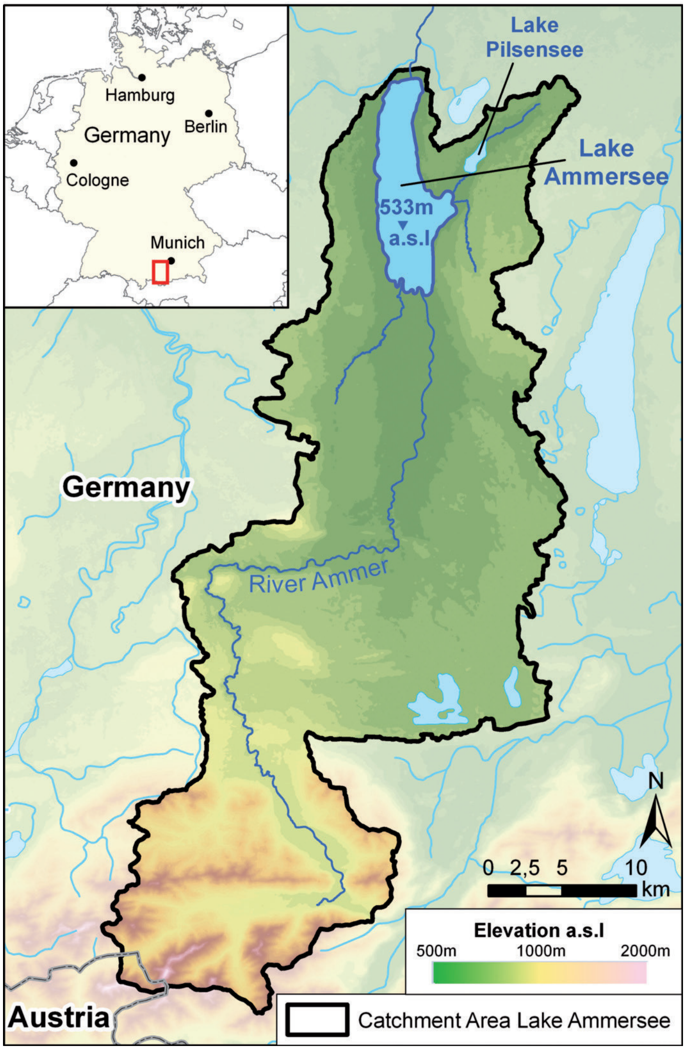

Fig. 1: Catchment area and elevation of Lake Ammersee (Source: Elevation data from ASTER GDEM, a product of METI and NASA)

the University of Western Australia (Imberger et al. 1978; Imberger and Patterson 1981). The model uses the Lagrangian approach of splitting and merging horizontal layers of uniform properties (temperature, salinity and density) (Imerito 2007). The limits of layer thicknesses are user-defined. The model output is the vertical distribution of lake water temperatures in the water column at the deepest point of the lake (83.7 m). The model requires meteorological (air temperature, precipitation, solar radiation, vapor pressure, cloud cover, and wind speed) and hydrological input data (see below) in daily resolution and information about the bathymetry. The model outputs are simulated water temperature profiles in a spatial resolution of < 1 m and temporally in daily resolution, too. Further details regarding the model in general, the process scheme and the input files can be found in our previous papers: Weinberger and Vetter (2012), Bueche and Vetter (2014), Bueche and Vetter (in revision), and Weinberger and Vetter (2014). Antenucci and Imerito (2003) provide a precise description of the variable model parameters stored in the input files, as well as the equations used for the model calculations.

In this investigation, only additional subsurface inflows were implemented; all other hydrological and meteorological input data as well as the simulation period (2002–2007) were not modified from the final settings of the model calibration. Hydrological inflow characteristics are described in DYRESM in terms of discharge (volume), temperature, and salinity; inflows can also be further defined either as surface inflow, which always enters

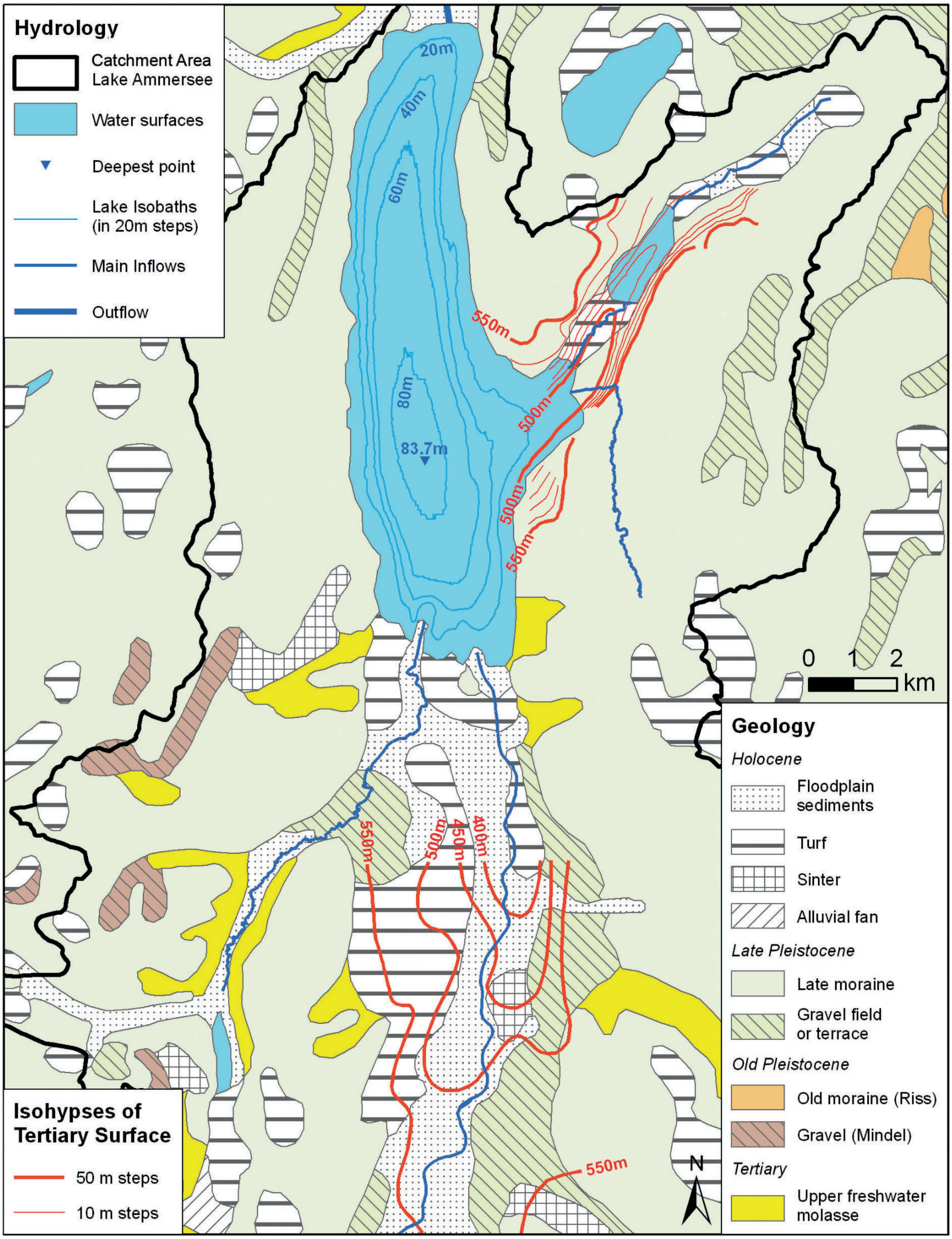

Fig. 2: Geology of the study area showing the major surface inflows to Lake Ammersee and the contour lines of the Tertiary surface (Source geo-data: Bavarian Surveying Authority/Bavarian Soil Information System)

the lake at the varying level of the surface height, or as sub-terrestrial inflow at a fixed height above the lake bottom.

Following limitations have to be considered when simulating lake water temperatures with DYRESM. The use of a constant light-extinction coefficient for the entire simulation period can result in an inaccurate projection of metalimnion temperatures (Gal et al. 2003; Bayer et al. 2013). This may induce an error in the simulation of hypolimnetic temperatures, especially during the summer stratification period (Bueche and Vetter 2014). Furthermore, shortages of the model are the limited capabilities of data post-processing and visualization.

3.2 Simulation scenarios

The present investigation was conducted assuming that the final settings resulting from the model calibration process deliver the optimal reproduction of real water temperatures when considering only surface inflow. A decrease in the error between the simulated and the real conditions in comparison to the results derived from calibration implementing various subsurface inflows could indicate an approximation to the real characteristics of all inflows. Scenarios were therefore created for the characteristics of the sub-terrestrial inflows and the settings improved iteratively. In total, 36 simulation runs were conducted in 6 succeeding groups and analyzed.

Groundwater temperature is roughly equivalent to annual average air temperature (Boehrer and Schultze 2008). In this investigation we assumed a constant water temperature for all sub-terrestrial inflow, which is not subject to change. Hence, all simulation runs were forced by the same water temperature for all subsurface inflows derived from the long-term average air temperature. To this end, the analysis of data series recorded at a meteorological station within the catchment area (1986–2010) and two stations (2002–2010) near the lake shore revealed a value of 8.65 °C.

For the other three variables the scenarios were created, a selection of which can be seen in table 1. The first digit in the scenario numbering system represents the group of simulation runs; the second number after the decimal point serves only to differentiate the scenarios within each group. The shown scenarios cover the variety of the inflow characteristics. The heights of the groundwater inflows are expressed in terms of depth (m) under the surface height of the initial profile (83.7 m), while salinity input data were either assumed to be equal to the observed surface inflow values or were set as constant values for the whole simulation period. The maximum volume of groundwater inflow was defined in advance by the execution of a water balance analysis in our previous calibration study (Bueche and Vetter 2014). The missing amount of total runoff was identified by subtracting all water influxes to the lake (the known inflow and precipitation) from all water effluxes (outflow and evaporation). During this analysis, ca. 257,000 m³ of unaccounted daily runoff for the lake outflow was identified to ensure a stable water balance. This amount represents both unknown smaller tributaries on the surface inflows and the total sub-terrestrial inflow. Hence, we assumed the volume of daily groundwater inflow to be a percentage of this amount and to be constant during the simulation period.

3.3 Statistical analysis

In-situ measurements of water temperatures in the vertical lake profile at the deepest point were available for the depths of 0–10 m in 2-m steps, for 10–20 m in 3-m steps, and for 20–80 in 10-m steps (in total 15 depths). The temporal resolution

Tab. 1: Selection of groundwater inflow scenarios

Scenario	2.1	3.1	3.5	4.5	4.7	4.8	4.9	5.2	6.1	6.2	6.3
Depth (m)	5	5	5/20	3	6	7	4/6	6/30	6	6	6
Volume (%)	50	50	50/20	70	70	70	35/35	70/5	70	65	75
Salinity	c	c	c/c	c	c	c	c/c	c/c	surf	c	c
[value] (PSU)	0.200	0.250	0.233	0.233	0.233	0.233	0.233	0.233	var	0.233	0.233

c = constant; surf = similar to surface inflow; var = variable of the field data is biweekly or monthly. For each date of the simulation period and depth the discrepancy between model-predicted and observed water temperatures – also known as bias error (BE) after Willmott and Matsuura (2005) – could be calculated. It can be assumed that the reproduction of real conditions via the model simulation is improved, when the magnitude of BE decreases. In order to quantify the alterations made between the simulation results of the final calibration run and those of the scenario runs, the difference in BE magnitude was calculated and summarized for each depth (Sum of magnitude differences of BE; SMD). Negative SMD values therefore represent an improvement in the reproduction of real conditions in relation to the results of the final calibration run. In addition the non-negative statistic root mean square error (RMSE) was calculated for each simulation run; larger RMSE values indicate a higher variability of the distribution of error magnitudes (Legates and McCabe 1999; Willmott and Matsuura 2005).

4 Results

In comparison to the simulations produced after the final calibration without subsurface inflow data (hereafter: calibration), the greatest decrease in error when simulating lake water temperatures was attained by the application of scenario 4.7, which involves one groundwater inflow at a depth of 6 m, with a constant salinity of 0.233, and a volume representing 70% of total unknown lake inflow. SMD and RMSE values, as well as the differences in RMSE values with respect to the calibration for 15 depths and the volume weighted total for the entire water column, are shown in figure 3. The same scenarios are specified as in table 1. In order to simplify the interpretation of the statistics, negative SMD values indicating an improvement in the reproduction of real conditions are colored green, with positive SMD values indicating the opposite displayed in red. Differences in RMSE values are colored in a similar way; the more intense the shade, the greater is the deviation in the simulation results. As

Scenario	Cal	2.1	3.1	3.5	4.5	4.7	4.8	4.9	5.2	6.1	6.2	6.3
SMD (K)												
Depth (m) 0m		1.98	3.56	3.51	0.67	-1.16	-0.64	1.18	1.21	0.76	0.03	0.46
2m		1.59	5.25	5.73	2.46	-0.57	0.89	0.74	3.23	0.36	1.31	1.61
4m		3.54	5.35	3.42	1.65	-0.01	-0.61	-0.18	3.96	0.19	2.06	1.31
6m		-1.87	7.55	0.78	1.18	-1.08	-0.37	-4.50	2.92	1.06	3.49	2.43
8m		-2.57	-2.53	-2.32	0.64	-3.16	-3.97	-4.99	-1.16	-1.77	-2.62	-0.84
10m		-0.74	4.74	3.45	-1.07	-4.27	-8.76	-3.60	-4.16	-0.74	-8.74	0.15
13m		-1.80	-8.32	4.07	-0.90	-2.78	-1.97	-3.29	-5.37	-0.72	-3.11	0.68
16m		-1.41	-5.76	-2.64	-6.02	-0.19	-2.63	-3.26	-3.90	-0.17	0.27	-1.28
20m		0.36	5.60	2.12	2.39	0.52	-2.98	2.15	0.48	1.79	0.51	-0.95
30m		0.05	0.96	0.23	-2.14	-2.10	-1.03	-0.89	-1.87	2.72	0.59	-1.79
40m		-0.67	0.69	-0.20	-1.77	-1.52	0.00	-1.24	0.28	0.78	1.15	0.58
50m		-0.80	0.66	-0.39	-0.45	-0.66	-0.20	-0.94	0.05	1.08	1.22	0.65
60m		-0.68	0.57	-0.38	-0.63	-0.60	-0.14	-0.70	-0.21	1.13	1.02	0.40
70m		-0.30	0.41	0.01	-0.26	-0.65	-0.14	-0.70	0.16	1.41	1.12	0.61
80m		-0.20	0.38	0.21	-0.04	-0.70	0.58	-0.12	0.32	1.65	1.23	0.99
total		**-4.55**	**19.44**	**13.83**	**-7.28**	**-17.99**	**-21.51**	**-16.37**	**-7.07**	**13.98**	**2.34**	**0.44**

Scenario	Cal	2.1		3.1		3.5		4.5		4.7		4.8		4.9		5.2		6.1		6.2		6.3	
RMSE (K)	RMSE	RMSE	Δ	RMSE	Δ	RMSE	Δ	RMSE	Δ	RMSE	Δ	RMSE	Δ	RMSE	Δ	RMSE	Δ	RMSE	Δ	RMSE	Δ	RMSE	Δ
Depth (m) 0m	1.14	1.19	0.05	1.22	0.08	1.18	0.04	1.16	0.02	1.13	-0.01	1.14	0.01	1.16	0.02	1.17	0.04	1.17	0.03	1.15	0.01	1.14	0.00
2m	1.00	1.05	0.05	1.09	0.10	1.06	0.07	1.04	0.04	0.97	-0.02	1.01	0.01	1.02	0.03	1.05	0.06	1.02	0.03	1.02	0.02	1.04	0.04
4m	0.89	0.94	0.05	0.97	0.08	0.90	0.01	0.91	0.02	0.86	-0.03	0.86	-0.03	0.88	-0.01	0.92	0.03	0.89	0.00	0.92	0.03	0.89	0.00
6m	1.07	1.01	-0.05	1.10	0.03	0.95	-0.12	1.06	-0.01	1.05	-0.02	1.02	-0.05	0.95	-0.11	1.12	0.06	0.98	-0.09	1.02	-0.05	1.01	-0.05
8m	1.53	1.34	-0.19	1.36	-0.16	1.24	-0.29	1.46	-0.07	1.31	-0.21	1.30	-0.22	1.28	-0.24	1.16	-0.37	1.42	-0.10	1.32	-0.21	1.36	-0.16
10m	1.40	1.24	-0.16	1.39	-0.01	1.35	-0.05	1.33	-0.07	1.23	-0.17	1.17	-0.23	1.25	-0.16	1.21	-0.19	1.13	-0.27	1.18	-0.22	1.23	-0.17
13m	1.79	1.78	-0.01	1.44	-0.34	1.66	-0.13	1.84	0.05	1.72	-0.06	1.73	-0.05	1.65	-0.13	1.52	-0.27	1.80	0.01	1.72	-0.06	1.80	0.01
16m	1.42	1.34	-0.08	1.03	-0.39	1.19	-0.23	1.18	-0.24	1.38	-0.04	1.28	-0.14	1.29	-0.13	1.18	-0.24	1.38	-0.04	1.41	-0.01	1.28	-0.14
20m	1.12	1.10	-0.03	1.18	0.06	1.13	0.01	1.11	-0.02	1.11	-0.02	1.03	-0.10	1.07	-0.06	1.07	-0.05	1.10	-0.03	1.11	-0.02	1.04	-0.08
30m	0.99	0.99	0.00	0.99	0.00	0.99	0.00	0.95	-0.04	0.96	-0.03	0.97	-0.02	0.96	-0.03	0.95	-0.04	1.04	0.05	1.00	0.01	0.95	-0.04
40m	0.78	0.76	-0.02	0.79	0.00	0.77	-0.01	0.75	-0.03	0.75	-0.03	0.78	-0.01	0.75	-0.03	0.78	0.00	0.79	0.00	0.79	0.01	0.79	0.00
50m	0.66	0.64	-0.02	0.67	0.01	0.64	-0.01	0.63	-0.02	0.63	-0.02	0.65	-0.01	0.64	-0.02	0.65	-0.01	0.67	0.02	0.67	0.01	0.66	0.00
60m	0.64	0.62	-0.02	0.65	0.01	0.63	-0.01	0.62	-0.02	0.62	-0.02	0.63	-0.01	0.63	-0.02	0.63	-0.01	0.66	0.02	0.65	0.01	0.64	0.00
70m	0.61	0.59	-0.02	0.62	0.00	0.59	-0.02	0.58	-0.03	0.59	-0.02	0.60	-0.01	0.60	-0.01	0.60	-0.02	0.62	0.01	0.61	0.00	0.61	-0.01
80m	0.62	0.60	-0.03	0.62	0.00	0.60	-0.02	0.59	-0.03	0.61	-0.02	0.61	-0.01	0.60	-0.02	0.60	-0.02	0.63	0.00	0.62	-0.01	0.62	-0.01
total	**1.01**	**0.98**	**-0.03**	**0.98**	**-0.03**	**0.97**	**-0.04**	**0.98**	**-0.03**	**0.97**	**-0.04**	**0.96**	**-0.05**	**0.96**	**-0.06**	**0.95**	**-0.06**	**1.00**	**-0.01**	**0.99**	**-0.02**	**0.97**	**-0.04**

Scale of RMSE (K): 0 – 1.5 – 3

Fig. 3: SMD, RMSE and differences in RMSE values for simulation results of a selection of scenarios for the groundwater inflow characteristic (specified in Tab. 1). The statistics are given for 15 depths and the volume weighted mean of the total water column

the figure shows, scenario (sc.) 4.7 yields negative SMD values for the entire lake profile with the exception of a small positive value for a depth of 20 m. Moreover, this simulation setting resulted in a reduction in the RMSE at all depths. The simulation results for all other scenarios exhibit at least for some depths, either positive SMD or higher RMSE values, or even both.

The constant salinity value of 0.233 represents the average for the observed surface inflow during the simulation period. Varying salinity input values equal to those of observed surface inflow (e. g. sc. 6.1) induced no better reproduction, as demonstrated by the mainly positive SMD values in the water column. For water temperatures simulated using a higher constant salinity value of 0.25 (sc. 3.1), although the highest RMSE values at depths of 8–16 m were reduced, very high positive SMD values occurred at the epilimnion and for the total value. Smaller constant salinity values (e.g. sc. 2.1: 0.20) resulted in mostly negative SMD values, but high positive values at depths of 0–4 m indicate no improvement in the reproduction by the simulation.

The statistics calculated for deep inflows at over 10 m depth (data not shown) revealed degradation in reproduction quality. For shallower depths of groundwater inflow (< 10 m), the use of a depth of 6 m, which is equivalent to a height of 77 m above the lake bottom, resulted in the best improvement (compare to sc. 4.5 and 4.8). Scenarios involving two different inflow depths (sc. 3.5, 5.2), one shallow and one under the thermocline (deeper than 20 m (Bueche and Vetter in revision)) respectively, also led to a particularly significant degradation of the simulation results. This is especially true at depths of 0–6 m, represented by high positive SMD values. Scenario 4.9, whose two subsurface inflows at shallow depths (4 m and 6 m) are supposed to represent the fact that such flows probably enter the water body across a whole layer and not at single one point, is associated with a noticeable improvement in reproduction accuracy within the depth range of 6–16 m (layer which nearly falls entirely within the metalimnion), with SMD values smaller than -3.20 K and a decrease in RMSE values by more than 0.1 K. However, relative to that of scenario 4.7 the quality of reproduction at the lake surface is degraded.

The scenarios simulating less (sc. 6.2: 65%) or more (sc. 6.3: 75%) than 70% of the unknown inflow amount resulted in distinct decreases in the accuracy of water temperature reproduction, with positive SMD values observed down almost the entire water profile. The same result was the case when an even lower (< 65%) or greater (> 75%) inflow volume was simulated (not shown).

The degree of alteration of the three varied inflow variables (volume, depth, and salinity) can hardly be quantified due to their different value ranges and units. Hence, no separate sensitivity analysis is performed for the simulation of water temperatures. Nevertheless, the simulation results attest a high sensitivity for all three parameters. As discussed above on the scenarios 6.2 and 6.3, a modified groundwater inflow of 5% induces significant deviations in the simulation results. The same applies to the salinity of the inflow (compare sc. 2.1 and 3.1) and the depth (e.g. sc 4.7 and 4.8).

Detailed differences between the simulated water temperatures produced by the calibration runs and scenario 4.7 and those derived from in-situ measurement are displayed in figure 4 for each date of observation during the simulation period. Regarding surface (0 m) temperatures, only slight deviations (improved and decreased accuracy) from the two simulations were induced by the application of sc. 4.7., although higher divergences (> 0.5 K) are always associated with a reduction in bias, e.g. for the summers of 2006 and 2007. At a depth of 8 m, peak differences in the simulated water temperatures, which occur during the summer months, were distinctively reduced, with a maximum deviation decrease of around 2 K (2004). The highest RMSE value for the entire water column was calculated for the calibration at 13 m depth. After applying scenario 4.7, although the maximum RMSE was again observed at 13 m, the graph of temperature differences reveals only moderate deviations from in-situ measurements, both increasing and decreasing almost in balance. Regarding hypolimnion temperatures, represented by the 40 m line in figure 4, only slight deviations were induced by implementing groundwater inflow, with a constant error reduction observed for the period 2005–2007.

The spatial pattern of water body temperature alterations after the implementation of sc. 4.7 is presented in figure 5. Figure 5a illustrates the discrepancy (i.e. error) between calibration and in-situ data. An analysis of this figure reveals an overestimation of upper water body temperatures (0–20 m) for the months June-October, with a maximum in September. For the rest of the year and within the hypolimnion (20 m to bottom) in general, this simulation yields an underestimation. Figures 5a and b, the latter of which displays the differences between simulated and calibration water temperatures, to-

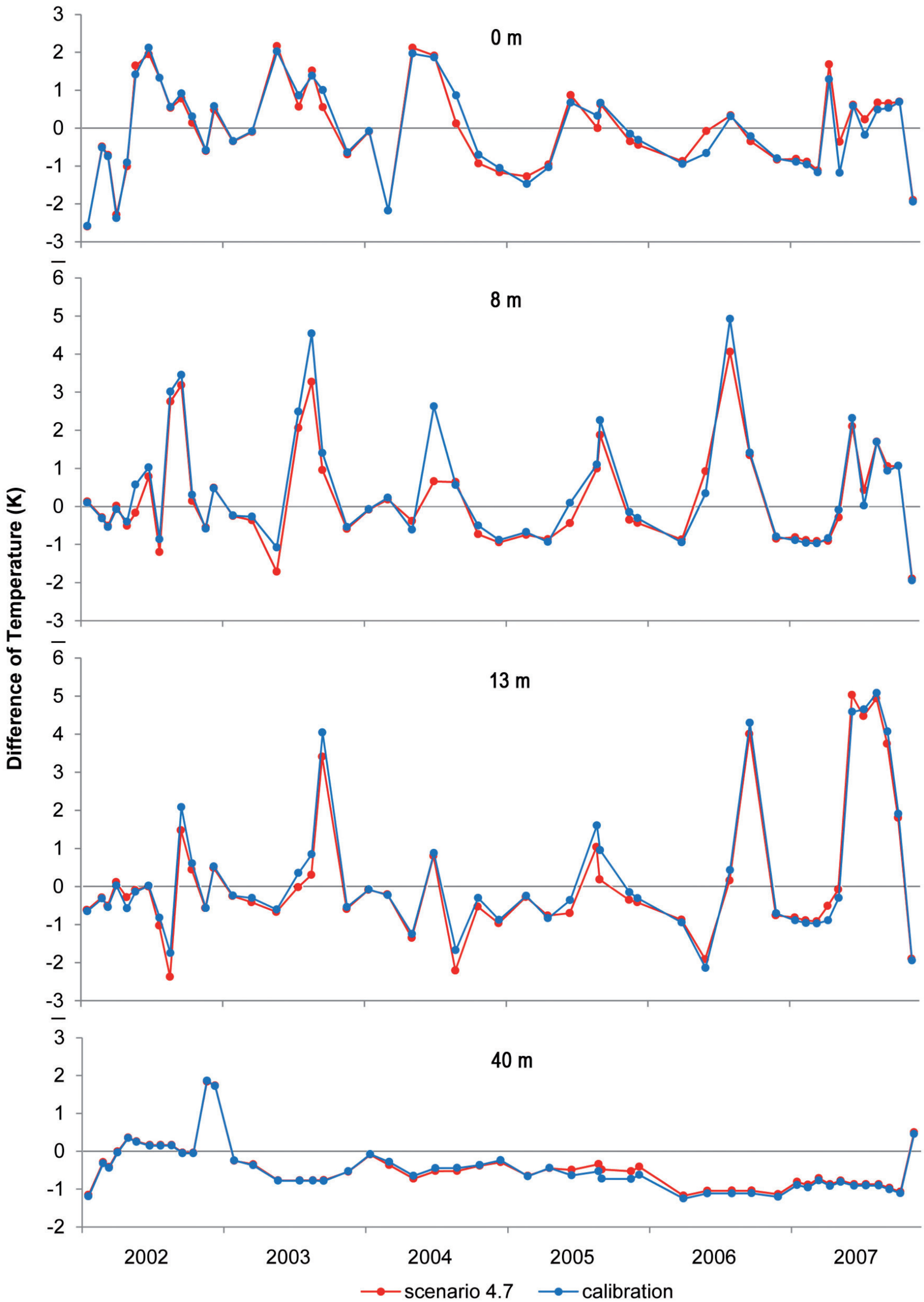

Fig. 4: Deviation of simulated water temperatures (calibration and scenario 4.7) from in-situ measurements for depths of 0, 8, 13, and 40 m

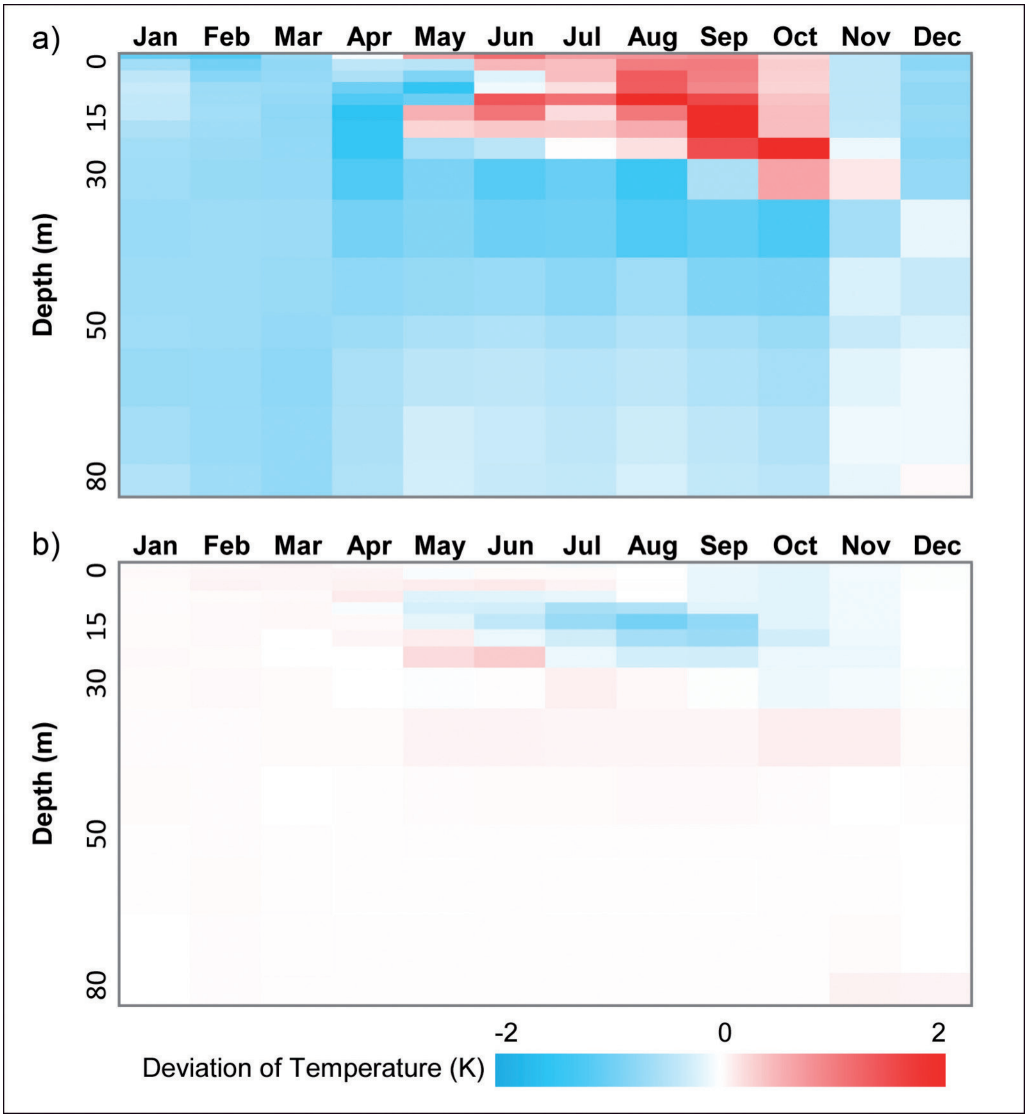

Fig. 5: (a) Monthly deviation averages of simulated (calibration) water temperatures and (b) the alterations induced by scenario 4.7

gether indicate that the reduction in deviations observed after the simulation of water temperatures is not only considerable (up to 1 K), but that it also occurs in a converse spatial pattern, i.e. a reduction in overestimated periods and layers, and an increase in underestimated water temperatures.

5 Discussion and conclusion

The inclusion of subsurface inflow in the one-dimensional hydrodynamic simulation of Lake Ammersee (see also Fig. 1) led to a considerably improvement in the reproduction of observed water temperatures in comparison to the simulation considering only surface inflows. This shows that DYRESM provides reliable simulation results considering groundwater inflows. Furthermore, the diverging modeling results for the applied scenarios attest a sensitivity of the model to varying groundwater inflow characteristics (Fig. 3).

The best error reduction in the reproduction of the water temperatures was identified in the simulation results for the groundwater inflow characteristics of scenario 4.7. Applying this scenario, a reduction in simulation deviation for almost all depths was achieved, represented by negative SMD values (with the exception of 20 m depth), a decrease in RSME values for the whole simulation period at all depths (Fig. 3), as well as alterations in the monthly averaged deviations as depicted in figure 5. The high degree of this improvement is reaffirmed by the reduction in error within the metalimnion during the summer stratification period. According to Perroud et al. (2009), this particular error can be ascribed to the fact that DYRESM tends to simulate the vertical position of the thermocline at too great depth, especially for the late season. Such an effect could have been reduced by the input of colder water during summer via subsurface inflow, resulting in a shallower thermocline. In comparison to the decrease in error for this depth and season, the slight increase in temperature overestimation for near-surface layers in May and June and the intensified underestimation for a depth of around 10 m during May is slight and not significant. Regarding the general error reduction, the induced decrease in the underestimation of water temperatures in the hypolimnion and throughout the entire water column during winter is not negligible. As a result of the almost constant winter water temperature of around 4 °C, these latter alterations, albeit slight, can be considered a considerable improvement in simulation, especially as this improvement is almost consistent for the mentioned depths/months.

The total SMD value of 4.8 is even smaller than that of 4.7. However, the statistics show two positive values (2 m, 80 m), one more and both higher than SMD values for sc. 4.7. The simulation results produced using the settings of sc. 4.7 providing a better reproduction of observed water temperatures.

The achieved notable improvement is not only represented by the averages of error values, but especially by the spatial and temporal pattern in the annual cycle of errors in the simulated water temperatures (Fig. 5). The implementation of groundwater inflow (sc. 4.7) induced a smoothing of the deviations of the calibration with only very rare and slight exceptions. Although yielding also a high reduction in SMD values, the results of scenario 4.9 show exceptions of smoothing for more data and depths (monthly resolution, data not shown), e.g. an increase of error at the surface, a weaker improvement in the hypolimnion layers and an enhanced underestimation of metalimnion temperatures.

As mentioned in section 2 and as shown in figure 2, the sediments found along the pathways designated for groundwater inflow to the south and east of the lake, including in the region around the Lake Pilsensee draining tributary, are Holocene floodplain sediments and lacustrine clays, which are generally considered as aquicludes due to the very small pore space (Krause 2001). Close to the lake shore, these sediments are mainly covered by turf and moorland, confirming their impermeability. The identified inflow depth of 6 m thus correlates with such hydro-geological conditions in which inflow at higher depths can be seen as negligible. The sc. 4.9 and 4.8 differ to sc. 4.7 only in the depth of inflow (see Tab. 1) varying in a moderate range around 6 m (+1 m for sc. 4.8, -2 m for the half of the inflow amount for sc. 4.9). The only slight improvement of the corresponding simulation results validates an inflow depth of about 6 m.

The best improvement in simulation results was achieved using a constant salinity value throughout the entire simulation period. One explanation for this could be that the time-variable parameter of nutrient input (here represented by salinity) can be projected only via the salinity of surface runoff. The salinity of subsurface inflows is buffered to the long-term average due to the longer retention period of water in the ground, as represented in the simulation input value used in scenario 4.7. However, the precision (three decimals) of the identified salinity value of 0.233 (sc. 4.7) results from averaging the surface inflow data and can only be considered as an approximation.

The result of using a discharge of 70% of unknown runoff during the simulation period cannot be verified by other references in the context of the present investigation. But the remaining 30% of unknown runoff for smaller surface inflows seems to be a realistic assumption. Furthermore it can be assumed that the input of a daily constant discharge is highly applicable to subsurface inflows. Long term variations are not projected in this approach, but intense fluctuations of subsurface discharge are hardly expected in the humid climate of the study area (Kunstmann et al. 2005).

The one-dimensionality of DYRESM is a simplified approach of processes in a lake, but it is very appropriate for the simulation of the vertical distribution of lake water temperatures (Joehnk and Umlauf 2001), especially for lakes with a simple bathymetry such as Lake Ammersee. The preparation of semi-automatic output data processing and visualizing tools enabled a rapid and expedient analysis of the simulation results for this study.

The inclusion of groundwater inflow in the simulation of water temperatures using DYRESM represents a simplified reproduction of real conditions. The identified characteristics of subsurface inflow are therefore only a preliminary approximation and cannot replace detailed hydro-geological investigation. Nevertheless, the results can provide a reliable basic idea of site conditions which have not previously been described in the literature. This simulation approach enables an economical and expeditiously investigation without any measurement campaign of groundwater data. Moreover, such a method is adequate for use in 1-D simulations, as the direction from which subsurface inflows enter the lake is not relevant to this type of modeling approach.

In the present study, an improvement in the reproduction of real-temperature conditions was obtained via the inclusion of subsurface inflow in hydrodynamic modeling using DYRESM. These results thus demonstrate that the latter model can be employed to simulate lake water temperatures when considering groundwater inflow.

It was also possible to roughly estimate the characteristics of groundwater inflows into Lake Ammersee by identifying the most accurate simulation results of those produced by different sub-terrestrial inflow scenarios. In combination with a review of currently available information regarding the geology of the Ammersee basin, obtaining an idea of actual subsurface inflow into the lake should provide a sound basis for further detailed investigation. The next step should be the validation of the characteristics of groundwater fluxes, which were obtained by this simulation approach, with field measurements to involve then the results to a simulation of the chemo-dynamics of Lake Ammersee, e.g. by applying the General Lake Model – Framework for Aquatic Biochemical Models (GLM-FABM).

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References

Adrian, R.; O'Reilly, C. M.; Zagarese, H.; Baines, S. B.; Hessen, D. O.; Keller, W.; Livingstone, D. M.; Sommaruga, R.; Straile, D.; Van Donk, E.; Weyhenmeyer, G. A. and Winder, M. (2009): Lakes as sentinels of climate change. In: Limnology and Oceanography 54, 2283–2297. DOI: 10.4319/lo.2009.54.6_part_2.2283

Alefs, J.; Muller, J. and Lenhart, B. (1996): Year to year changes of the diatom assemblage since 1958 in dated varves of a sediment core from Lake Ammersee (Bavaria). In: Limnologica 26, 39–48.

Antenucci, J. and Imerito, A. (2003): Dynamic Reservoir Simulation Model – DYRESM: User Manual. http://www.cwr.uwa.edu.au/services/models/reference/dyresm/DYRESM_UsersManual.pdf (Date: 31 January 2013)

Bayer, T. K.; Burns, C. W. and Schallenberg, M. (2013): Application of a numerical model to predict impacts of climate change on water temperatures in two deep, oligotrophic lakes in New Zealand. In: Hydrobiologia, 1–19. DOI: 10.1007/s10750-013-1492-y

Boehrer, B. and Schultze, M. (2008): Stratification of lakes. In: Reviews of Geophysics. 46, RG2005. DOI: 10.1029/2006rg000210

Bueche, T. and Vetter, M. (2014): Simulating water temperatures and stratification of a pre-alpine lake with a hydrodynamic model: calibration and sensitivity analysis of climatic input parameters. In: Hydrological Processes 28 (3), 1450–1464. DOI: 10.1002/hyp.9687

– (in revision): Future alterations of thermal characteristics in a medium-sized lake simulated by coupling a regional climate model with a lake model. In: Climate Dynamics.

Czymzik, M.; Dulski, P.; Plessen, B.; von Grafenstein, U.; Naumann, R. and Brauer, A. (2010): A 450 year record of spring-summer flood layers in annually laminated sediments from Lake Ammersee (Southern Germany). In: Water Resources Research 46, W11528. DOI: 10.1029/2009WR008360

Danis, P.-A.; von Grafenstein, U. and Masson-Delmotte, V. (2003): Sensitivity of deep lake temperature to past and future climatic changes: a modeling study for Lac d'Annecy, France, and Ammersee, Germany. In: Journal of Geophysical Research 108, 4609. DOI: 10.1029/2003jd003595

Danis, P.-A.; von Grafenstein, U.; Masson-Delmotte, V.; Planton, S.; Gerdeaux, D. and Moisselin, J. M. (2004): Vulnerability of two European lakes in response to future climatic changes. In: Geophysical Research Letters, L21507, 1–4. DOI: 10.1029/2004gl020833

Dokulil, M. T.; Jagsch, A.; George, G. D.; Anneville, O.; Jankowski, T.; Wahl, B.; Lenhart, B.; Blenckner, T. and Teubner, K. (2006): Twenty years of spatially coherent deepwater warming in lakes across Europe related to the North Atlantic Oscillation. In: Limnology and Oceanography 51, 2787–2793.

Gal, G.; Imberger, J.; Zohary, T.; Antenucci, J.; Anis, A. and Rosenberg, T. (2003): Simulating the thermal dynamics of Lake Kinneret. In: Ecological Modelling 162, 69–86. DOI: 10.1016/s0304-3800(02)00380-0

Imberger, J. and Patterson, J. C. (1981): A Dynamic Reservoir Simulation Model – DYRESM 5. New York.

Imberger, J.; Patterson, J. C.; Hebbert, B. and Loh, I. (1978): Dynamics of reservoir of medium size. In: Journal of Fluid Mechanics 78, 489–512.

Imerito, A. (2007): Dynamic Reservoir Simulation Model DYRESM v4. University of Western Australia.

Jerz, H. (1993): Erläuterungen zur Geologischen Karte von Bayern 1:25 000, Blatt Nr. 8132 Weilheim. München.

Joehnk, K. D. and Umlauf, L. (2001): Modelling the metalimnetic oxygen minimum in a medium sized alpine lake. In: Ecological Modelling 136, 67–80. DOI: 10.1016/s0304-3800(00)00381-1

Krause, K.-H. (2001): Die geologisch-hydrogeologische Situation im Jung- und Altmoränengebiet des Andechser Höhenrückens zwischen Ammer- und Würmsee und in der nördlich angrenzenden Wurzelzone der westlichen Münchener Schotterebene (Oberbayern). PhD thesis. München.

Kucklentz, V. (2001): Antwort bayerischer Voralpenseen auf verringerte Nährstoffzufuhr. München.

Kunstmann, H.; Krause, J. and Mayr, S. (2005): Inverse distributed hydrological modelling of alpine catchments. In: Hydrology and Earth System Sciences Discussions 2, 2581–2623.

Legates, D. R. and McCabe, G. J., Jr. (1999): Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. In: Water Resources Research 35, 233–241. DOI: 10.1029/1998wr900018

Legesse, D.; Vallet-Coulomb, C. and Gasse, F. (2004): Analysis of the hydrological response of a tropical terminal lake, Lake Abiyata (Main Ethiopian Rift Valley) to changes in climate and human activities. In: Hydrological Processes 18, 487–504. DOI: 10.1002/hyp.1334

Lenhart, B. (1987): Limnologische Studien am Ammersee 1984–1986. In: Informationsberichte des bayerischen Landesamtes für Wasserwirtschaft 87, 1–112.

Niedda, M. and Pirastru, M. (2013): Hydrological processes of a closed catchment-lake system in a semi-arid Mediterranean environment. In: Hydrological Processes 27 (25), 3617–3626. DOI: 10.1002/hyp.9478

Perroud, M.; Goyette, S.; Martynov, A.; Beniston, M. and Anneville, O. (2009): Simulation of multiannual thermal profiles in deep Lake Geneva: a comparison of one-dimensional lake models. In: Limnology and Oceanography 54 (5), 1574–1594. DOI: 10.4319/lo.2009.54.5.1574

Rinke, K.; Yeates, P. and Rothhaupt, K. O. (2010): A simulation study of the feedback of phytoplankton on thermal structure via light extinction. In: Freshwater Biology 55, 1674-1693. DOI: 10.1111/j.1365-2427.2010.02401.x

Schaumburg, J. (1996): Seen in Bayern – Limnologische Entwicklung von 1980 bis 1994. In: Informationsberichte des bayerischen Landesamtes für Wasserwirtschaft 96, 1–216.

Tanentzap, A. J.; Hamilton, D. P. and Yan, N. D. (2007): Calibrating the Dynamic Reservoir Simulation Model (DYRESM) and filling required data gaps for one-dimensional thermal profile predictions in a boreal lake. In: Limnology and Oceanography: Methods 5, 484–494.

Vetter, M. and Sousa, A. (2012): Past and current trophic development in Lake Ammersee – Alterations in a normal range or possible signals of climate change? In: Fundamental and Applied Limnology 180, 41–57. DOI: 10.1127/1863-9135/2012/0123

Weinberger, S. and Vetter, M. (2012): Using the hydrodynamic model DYRESM based on results of a regional climate model to estimate water temperature changes at Lake Ammersee. In: Ecological Modelling 244, 38–48. DOI: 10.1016/j.ecolmodel.2012.06.016

– (2014): Lake heat content and stability variation due to climate change: coupled regional climate model (REMO)-lake model (DYRESM) analysis. In: Journal of Limnology 73 (1). DOI: 10.4081/jlimnol.2014.668

Williamson, C. E.; Saros, J. E. and Schindler, D. W. (2009): Sentinels of change. In: Science 323, 887–888. DOI: 10.1126/science.1169443

Willmott, C. J. and Matsuura, K. (2005): Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. In: Climate Research 30, 79–82. DOI: 10.3354/cr030079

Wolf, J. (2006): Räumlich differenzierte Modellierung der Grundwasserströmung alluvialer Aquifere für mesoskalige Einzugsgebiete. PhD thesis. Stuttgart

Woo, M.-K. and Mielko, C. (2007): An integrated framework of lake-stream connectivity for a semi-arid, subarctic environment. In: Hydrological Processes 21, 2668–2674. DOI: 10.1002/hyp.6789

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