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HYDRAULIC MANAGEMENT DRIVES HEAT BUDGETS AND TEMPERATURE TRENDS IN A MEDITERRANEAN RESERVOIR

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ABSTRACT

By contrast to the more regular and predictable temperate lakes, heat budgets and temperature dynamics in Mediterranean reservoirs are characterized by a marked interannual variability. In the present paper, the heat content, annual Birgean heat budget (ABHB), and thermal structure of Sau Reservoir were examined during a period of hypolimnetic withdrawal between 1980 and 1985, and during a period of withdrawal at intermediate depths between 1996 and 2004. The two study periods were also characterized by a wide range of stored water volume fluctuations. Results were used to develop and validate an empirical model to predict annual and monthly heat dynamics statistics and mixed layer depth as a function of hydraulic management parameters such as water volume and selective withdrawal depth. During the hypolimnetic withdrawal period elevated ABHB and deep mixed layer depths were recorded in the reservoir, which behaved as a heat trap. By contrast, intermediate depth withdrawal promoted a shallower and more stable thermocline, thus increasing the cold hypolimnetic water volume and decreasing heat content and ABHB. The study reveals that hydraulic management constitutes the main driver of the heat and thermal dynamics in reservoirs with multiple withdrawal outlets. By contrast with the increasing temperature trends recorded in many natural lakes, the hydraulic management in Sau Reservoir induced a progressive reduction in water temperature and heat content in the system, thus partially counteracting the possible deleterious effects of global warming. Our intensive study in a single, highly-dynamic ecosystem constitutes a new approximation to the study of thermal structure and heat dynamics in water bodies.

1. INTRODUCTION

It is well-known that structure and function of lake and reservoir ecosystems are vertically-organized following the light-gravity axis (MARGALEF, 1983; FORD, 1990). The solar energy and the thermal radiation arriving to the water surface are quickly transformed into heat in the upper layers of the water column. At the same time, the wind-driven turbulent kinetic energy spreads this absorbed heat in all three dimensions of the water body. The resulting vertical density gradient (mainly consequence of temperature change) acts as a resistance factor against water column mixing.

From a thermodynamics scope, lentic ecosystems can be considered as thermal engines that exchange heat with their surroundings, and their evolution can be characterized by the development of their heat content, heat budgets, and average temperature. Since the pioneer work by BIRGE (1915), many studies have collected information about the heat dynamics on numerous lakes around the world, covering both temperate lakes (HUTCHINSON, 1957; STEWARD, 1973; BLATON, 1973; WETZEL, 1983; ALLOT, 1986), tropical lakes (TALLING, 1966; LEWIS, 1973; HENRY and BARBOSA, 1989; ARCIFA *et al.*, 1990; HENRY, 1993; TUNDISI, 1984), and subartic lakes (EDMUNSON and MAZUMDER, 2002). As a general result, in natural lakes the evolution of the heat content and the water column temperature follows a quite regular seasonal cycle as a consequence of an almost constant water volume (HUTCHINSON, 1957; WETZEL, 1983). By contrast, thermal dynamics of reservoirs could be more variable due to fluctuations in water storage volume and depth of water withdrawal.

The precise knowledge of reservoir physical dynamics results of paramount relevance for hydrobiological and water quality studies as physical control of the biotic structure in reservoirs is even more important than in natural lakes (UHLMANN, 1998). Water temperature and heat dynamics have significant influence on the water quality and ecology of lakes and reservoirs (WETZEL, 1983). Among others, they control the solubility of dissolved oxygen, the metabolism and the respiration of plants and animals, and the toxicity of pollutants (STEFAN *et al.*, 1998). Nowadays, it is well-known that the average temperature and heat content in lakes is progressively increasing as a result of global warming (CARPENTER *et al.*, 1992). In this context, empirical analyses on the response of aquatic systems to temperature increments suggest that global warming would lead to a general increase in lake productivity at all trophic levels (REGIER *et al.*, 1990), thus exacerbating hypolimnetic oxygen depletion, nutrient release from sediments, and eutrophication processes in productive ecosystems (BLUMBERG *et al*., 1990).

Consequently, an appropriate knowledge of the mechanisms governing the thermal structure and energy budgets in lentic ecosystems is of fundamental interest for water quality management, especially in the case of reservoirs with multiple withdrawal depths. In these systems, appropriate hydraulic management could work against the deleterious effects of climate change. In this sense, wise limnological and engineering management of reservoir water quality may be facilitated by adequate empirical models offering reliable predictions of the effects of alternative hydraulic management on the thermal structure and heat dynamics of the system.

In this paper, the thermal regime and the energy budget of a Mediterranean water supply reservoir (Sau Reservoir, Spain) have been intensively studied during two time periods (1980-85, and 1995-2003), characterized by a wide range of water volume fluctuations covering both dry and wet years. The depth of the water extraction outlet also changed from the deepest possibility during the 1980-95 period to the intermediate one since 1996.

The main objectives of the study are (i) to describe the temporal (monthly and annual) trends and fluctuations of heat content, annual Birgean heat budget (ABHB), and water temperature in Sau Reservoir; (ii) to reveal the paramount effect of hydraulic management on the heat and thermal properties of the reservoir; and (iii) to generate and validate an empirical model capable to explain and predict the heat and thermal dynamics of the reservoir only using hydraulic management parameters.

2. MATERIAL AND METHODS

2.1. Study site

Sau Reservoir is a Mediterranean water-supply, canyon-type reservoir located in a middle stretch of the Ter River (Catalonia, NE Iberian Peninsula). It was first filled in 1964, and since then its main limnological features have been intensively studied. Table 1 summarizes some of the main morphological, hydrological, and water quality features of the reservoir. The hydraulic management of Sau dam is based on the selective withdrawal of water at any of three different depths: an upper outlet (414 meters above sea level, m.a.s.l), an intermediate outlet (399 m.a.s.l), and a bottom outlet (389 m.a.s.l). Since 1996, the water extraction depth changed from the deepest outlet to the intermediate one.

Sau Reservoir is thermally classified as a warm monomictic system (BO-PING *et al.*, 2000). The water body experienced a process of increasing eutrophication (VIDAL and OM, 1993), from moderately eutrophic during the first years, to severe eutrophication during the early 1990s. Extended limnological descriptions and detailed processes in the reservoir can be found elsewhere (ARMENGOL *et al.*, 1986; VIDAL and OM, 1993; SOMMARUGA *et al.*, 1995; ŠIMEK *et al.*, 1998; ARMENGOL *et al.*, 1999; HAN *et al.*, 2000; COMERMA *et al.*, 2001; ŠIMEK *et al.*, 2001; GASOL *et al.*, 2002; ARMENGOL *et al.*, 2003; COMERMA *et al.*, 2003; RUEDA, 2006; RUEDA *et al.*, 2006; MARCÉ *et al.* 2006).

2.2. Thermodynamics measurements

The thermal structure of Sau Reservoir was described from monthly vertical temperature profiles at a sampling station located in the pelagic of the lacustrine zone. Data were recorded at 1 m depth intervals from the surface to the bottom using different devices (a PT100 thermistor until 1985, a YSI-Grant 3800 model Water Quality Logging System for 1994-95 period, and a Turo Water Quality Analyzer model T-611 from 1996 to 2004), all of them providing measurement accuracy of (at least) 0.1ºC. The present study focuses on data corresponding to two different periods of time (1980-85, and 1995-2003) that cover a wide range of hydrologic conditions. Additional data from the period 1967-1972, and from year 2004 were used during the validation process of an empirical model for heat content and temperature in the reservoir. The required information on the morphological and hydrological characteristics of Sau Reservoir (inflow, outflow, reservoir volume and surface) was supplied by the Catalan Water Authority (ACA).

The heat content (Q, cal) for a given water volume can be calculated by means of (CHAPRA and RECKHOW, 1983):

$$Q = t\rho CV \qquad (1)$$

where t is measured water temperature (ºC), ρ is water density (g cm^{-3}), C is the specific heat of water (cal g^{-1} $ºC^{-1}$), and V the water volume (cm^3). In order to transform our field temperature information into heat, it has been assumed that the volume of a gram of water is 1 ml, and that the specific heat of the water is 1 cal g^{-1} $ºC^{-1}$ (COLE, 1975; WETZEL and LIKENS, 1991; HENRY, 1993). The errors associated to these assumptions are negligible in the context of our results. Accordingly, for each monthly temperature profile, the heat content was calculated following the method described by WETZEL and LIKENS (1991) using the hypsographic curve (depth-area) facilitated by ACA:

$$Q_z = \sum_{z_0}^{z_{\max}} t_z A_z h_z \qquad (2)$$

where Q_z is the heat content (calories, latterly transformed to terajoules, TJ), t_z is the measured average temperature of an unity layer of thickness h_z (cm), and A_z is the average surface of the layer z (cm^2).

Heat content results were linearly interpolated to daily values, and then transformed into monthly averages. For every year, the annual Birgean heat budget (ABHB, MJ m^{-2}) was calculated according to:

$$B = \frac{Q_{\max} - Q_{\min}}{A_{med}} \qquad (3)$$

where Q_{max} and Q_{min} are the monthly maximum and minimum accumulated heat during the year, respectively, and A_{med} is the annual mean surface of Sau Reservoir (m^2). ABHB is a widely used proxy of the capacity of the reservoir to store energy during the year, and a synthesis of all the physical processes occurring in the air-water interface and within the water mass (MARTIN and McCUTCHON, 1999; AMBROSETTI and BARBANTI, 2002).

Finally, the mixed layer depth (Z_{mix}) was computed as the depth of maximum thermal stability defined by the frequency of Brunt-Väisälä (IMBERGER, 1998):

$$N = \sqrt{\frac{g}{\rho}\frac{d\rho}{dz}} \qquad (4)$$

where *g* is gravity acceleration.

3. RESULTS

3.1. Thermal stratification patterns

Thermal stratification in Sau Reservoir usually developed in late February to early March and lasted for 9 months (Fig. 1). Overturn generally took place around November, with little variation as a function of the rainfall intensity and the occurrence of the first snow episodes in the near-located Pyrenees (ARMENGOL *et al*., 1999).

In terms of thermal structure, the most striking difference between the 1980-85 and 1996-2003 periods was the intensity of the stratification and the location of the thermocline. During the first period a wide metalimnion with an unstable thermocline close to the bottom were apparent, whereas during the 1996-2003 period stratification was more intense, and the thermocline was located in the upper layers (Fig. 1). In the last case, the thermocline effectively isolated the hypolimnion from surface heat sources, thus greatly reducing the heat transfer into that portion of the reservoir. The hypolimnetic water temperature also reflected these differences. During the hypolimentic withdrawal interlude, temperatures in the hypolimnion ranged between

8.04 and 13.37º C depicting a whole-period mean value of 9.88 ± 0.11ºC (mean ± SE), while during the 1996-2003 period (i.e. with intermediate withdrawal) the hypolimnetic water temperature was lower and more constant, ranging between 6.69 and 9.80 ºC and showing a whole-period average of 7.72 ± 0.08ºC.

A very strong positive and statistically significant relationship was found between the water withdrawal depth and the mixed layer depth (Fig. 2). Using this linear regression, it was possible to estimate the mixed layer depth from the operational outlet depth:

$$Z_{mix/est} = 1.1485\, Z_{out} + 1.4556 \qquad (R^2 = 0.91;\ n = 73;\ p < 0.0001) \qquad (5)$$

where $Z_{mix/est}$ is the estimated mixed layer depth (m) and Z_{out} is the selective withdrawal depth (m).

3.2. Heat content, heat budget and average temperature

The intrannual fluctuation in the Sau Reservoir heat content was characterized by a very regular pattern (Fig. 3). The maximum heat content was mainly achieved during August and depicted a marked variability, ranging from 10552 TJ in 1980 to 4606 TJ in 1999. Conversely, the minimum heat content was more uniform and always occurred in February. Nevertheless, the interannual variability was high, and showed a clear differentiation of the last eight years, characterized by low heat content during summer. This difference, which was evident under very different water volume conditions (Fig. 3a), was explained by lower hypolimnetic temperatures and the smaller volume of the epilimnion recorded during the 1996-2003 period, both induced by the epilimnetic withdrawal operations. In 1999 the annual cycle of heat content was not as regular as in the neighbor years, due to the low water volume stored during summer months, which was one of the reservoir historical minima. As a result, the maximum monthly heat content occurred during June. In agreement to the previous results, ABHB ranged between 915 MJ m^{-2} in 2003 and 2197 MJ m^{-2} in 1981.

The mean water column temperature was characterized by a regular seasonal cycle depicting very low interannual variability (Fig. 4). The range of mean monthly temperatures for all the studied years oscillated between 21.69 ºC in September 1985 and 4.69 ºC in February 1999. Remarkably, the evolution of the mean annual water column temperature during the last eight years (1995-2003) did not follow the temporal pattern of the heat content (figs. 3b and 4a). In this specific period, when epilimnetic discharge was operative, both summer and annual average temperatures were lower than during the previous period, and a marked decreasing trend in water temperature was recorded (see Fig. 4a). The monthly averaged seasonal cycle of temperature obtained by combination of all collected data was characterized by a regular wave function (Fig. 5). Minimum monthly temperature was 6.97 ºC in February, and the maximum was recorded during September (18.4 ºC). Mean temperature for the whole study period was 12.86 ºC.

3.3. Empirical modeling the thermal dynamics, heat content, and heat budget in Sau Reservoir

All the above-exposed results were applied to build an empirical model capable to describe and predict the heat and temperature dynamics in Sau Reservoir using only hydraulic management features, such as the stored water volume and the selective withdrawal depth.

The most striking feature of our model was that all calculations depended on a single predictor variable: the operational withdrawal depth during August ($Z_{\text{out August}}$). All the other information needed was the seasonal cycle of monthly mean temperature in the reservoir (Fig. 5), and the monthly water volume (another quantity closely related to hydraulic management).

The model first described the average annual temperature in the reservoir (T_{mean}) as a linear function of $Z_{\text{out August}}$ (Fig. 6):

$$T_{\text{mean}} = 0.0795\, Z_{\text{out August}} + 11.104 \qquad (R^2 = 0.79;\ n=15;\ p<0.001) \qquad (6)$$

Then, a sinusoidal function was assumed for the monthly evolution of temperature during an average year. The fitted function (bold line in Fig. 5) was used to calculate monthly mean temperatures (T_M) for a given year in the reservoir, using the corresponding T_{mean} as the reference value:

$$T_M = T_{\text{mean}} + 5.94 \sin((2\pi M/12) + 3.69) \qquad (R^2 = 0.99;\ n=180;\ p<0.0001) \qquad (7)$$

where T_M is the reservoir mean temperature during the M month (M ranging between 1 and 12), and T_{mean} is the mean annual temperature calculated according to equation (6). The obtained model correctly simulated the time series of monthly temperatures in Sau Reservoir (Fig. 4b), using only $Z_{\text{out August}}$ as a predictor variable.

Once good estimates of monthly mean temperatures in the reservoir were available, these estimates could be combined with the monthly volume information to calculate heat contents and ABHBs. For a given year, the monthly heat content in the reservoir (Q_M) was estimated using:

$$Q_M = T_M V_M \qquad (R^2 = 0.93;\ n=180;\ p<0.0001) \qquad (8)$$

where V_M is the water volume in month M (M ranging between 1 and 12). The simulated monthly heat content values successfully fitted the measured time series for all the study period (Fig. 3b).

Finally, estimation of ABHBs was straightforward using results from Equation 8. The Birgean heat balance (B_{est}) for a given year was estimated using:

$$B_{est} = (Q_{max/est} - Q_{min/est}) / A_{med} \qquad (R^2 = 0.83\ ;\ n= 15\ ;\ p< 0.0001) \qquad (9)$$

where $Q_{max/est}$ and $Q_{min/est}$ are the are the monthly maximum and minimum accumulated heat during the year, as simulated by Equation 8. Again, the measured and simulated Birgean heat budgets where satisfactorily correlated along the whole study period (Fig. 7).

Model validation

The above-exposed numerical model was successfully validated against a four year data set during which the reservoir was submitted to hypolimnetic withdrawal (1967-1972), and another year when water was extracted from the intermediate outlet (2004). Note that no one of the validation time periods were considered in the model building process. The simulation results correctly followed the measured heat content, heat budget, and average temperature data during the validation period (Fig. 8). In addition, the Root Mean Square Error (RMSE) computed for the model calibration and validation periods were low and similar (Table 2), thus confirming the successful validation of the model.

4. DISCUSSION

Many of the seminal empirical studies dealing with heat dynamics and thermal structure in natural waters were based on empirical observations from as many natural lakes as possible. Most of these studies included systems extended over large areas of the world covering a wide range of morphometric characteristics such as surface area, mean depth, or water volume (BIRGE, 1915; HUTCHINSON, 1957; GORHAM, 1964; SCHINDLER, 1971; SHUTER *et al.*, 1983; PATALAS, 1984; HANNA, 1990; GELLER, 1992; AMBROSETTI and BARBANTI, 2001; AMBROSETTI and BARBANTI, 2002; EDMUNSON and MAZUMDER, 2002), degree of exposure and sheltering of lakes (HUTCHINSON, 1957), and wind fetch (SHUTER *et al.*, 1983; PATALAS, 1984; HANNA, 1990).

As a main conclusion, these studies established that morphometric and climatic features determine the depth of the thermocline and, consequently, the heat content and heat budget of lakes (HUTCHINSON, 1957; WETZEL, 1983; MAZUMDER and TAYLOR, 1994; EDMUNSON and MAZUMDER, 2002). In this context, HANNA (1990) evaluated the accuracy of 17 empirical models that predict the depth of the mixed layer from morphometric variables over a set of 123 temperate lakes (covering Canada, USA, Europe, Israel and New Zealand), and concluded that the wind fetch (or wind maximum effective length) constitutes the best Z_{mix} predictor in natural lakes. Similarly, GELLER (1992) concluded that wind fetch governed the heat budget of 24 Chilean lakes along a latitudinal transect through its control on Z_{mix}. EDMUNSON and MAZUMDER, 2002 reached similar results in a 60 subartic lakes. Although these comparative studies were crucial to reveal the factors and mechanisms involved in the thermal dynamics of lakes, they showed some limitations, since thermal profiles recorded (and consequently the heat budgets calculated) represented just point-in-time images of varying actual states.

Conversely, our study has provided a complete "moving" picture of the heat dynamics in a very dynamic ecosystem submitted to a wide range of hydraulic (i.e. water volume), morphological (i.e. fetch, surface area), and thermal (i.e. mixed layer depth) conditions along time. In addition to the hydrological variability characteristic of Mediterranean reservoirs, in Sau it is possible to modify the depth of the outflow by selecting one of the three outlets placed at different water levels. This is important because it is well-known that in reservoirs the thermocline location and stability are typically controlled by the depth of the operative outlet during summer (GROEGER and TIETJEN, 1998; CASAMITJANA *et al.*, 2003; JAMES *et al.*, 2004). However, to our knowledge this study constitutes the first empirical report of the direct influence of withdrawal depth on heat budgets and temperature trends in a man made reservoir using an extensive database, although some point-in-time studies already pointed in this direction (MARTIN and ARNESON, 1978).

Nevertheless, we found a positive and significant relationship between the water withdrawal depth and the mixed layer depth in Sau Reservoir. Interestingly, this regression was more accurate during the hypolimnetic withdrawal operation period, probably because the deeper thermocline was less susceptible to the turbulent mixing induced by meteorological events (i.e. wind stress) than a shallower one. In addition, the observed dynamics of the mixed layer depth in Sau was very different to that computed from wind fetch and morphometrical features following PATALAS (1961) (Fig. 9), thus evidencing that hydraulic management constituted the key driver of the reservoir thermal structure.

Thus, when Sau Reservoir was submitted to deep water extraction, a marked sinking of the thermocline by reduction of the hypolimnion volume was recorded, which has been previously nominated by TUNDISI (1984) as hydraulic stratification. Accordingly, when cold hypolimnetic water was released by the bottom outlet of Sau dam (from 1980 to 1995) the water column depicted a complex thermal structure characterized by a deep thermocline (between the 30 and 40 meters depth), a wide metalimnion, and a very narrow hypolimnion confined to the deepest layers of the water column. In agreement with STRASKRABA (1980), the enhanced epilimnion thickness resulted in the increasing of the mean water column temperature and the reservoir ABHB, and Sau behaved as a heat trap, accumulating heat in the wide mixing zone and losing cold hypolimnetic water through the bottom outlet. As a consequence, its mean ABHB (1514 MJ m^{-2} for the 1980-1995 period) was larger than such corresponding to lakes (MARGALEF, 1983; WETZEL, 1983) and reservoirs (MORENO-OSTOS, 2004) with similar morphometric characteristics, and only surpassed by very large lakes like Baikal, Eikeen, Ness, Geneva, Cayuga, Michigan, or Washington (HUTCHINSON, 1957; FREY, 1963; GORHAM, 1964, BLANTON, 1973; COLE, 1975; WETZEL, 1983; KALFF, 2002).

As a part of a whole ecosystem management strategy, since 1996 warm epilimnetic water was extracted through the intermediate outlet, promoting the development of a shallower and more stable thermocline (around 20 meters depth), the increase of the hypolimnetic volume, and the decrease of the mean water column temperature. As a consequence, Sau ABHB substantially decreased, showing an average value of 1009 MJ m^{-2} during the period 1996-2003, a value close to those recorded in morphologically similar temperate lakes and marginal subalpine European lakes (HUTCHINSON, 1957; MARGALEF, 1983). In fact, and as predicted by STRASKRABA (1998) through numerical simulations, the epilimnetic withdrawal proceeds comparable to the natural water bodies' surface-water outflow. Consequently, the mixed layer depth recorded during this period in Sau Reservoir was more similar to that expected for a natural lake (see Fig. 9). MORENO-OSTOS (2004) computed an analogous scenario in El Gergal Reservoir, a similar Mediterranean canyon-type ecosystem where epilimnetic withdrawal induced a well-established thermocline at 10-15 meters depth.

All these changes promoted significant water quality alterations in Sau Reservoir. As previously demonstrated by BARBIERO *et al*. (1997) and JAMES *et al.* (2004), discharging primarily from upper layers in the water column results in a strengthened thermal stability, thus contributing to reduce the potential for vertical entrainment of hypolimnetic nutrients for algal uptake. This mechanism has become especially effective in Sau Reservoir, where the rich-in-nutrients river inflow typically plunges directly to the hypolimnion via a density current (MARCE *et al.*, 2006). At the same time, the increased epilimnetic flushing rates may also be effective in removing algal populations from the system at a greater rate than their doubling time (PRIDMORE and McBRIDE, 1984; SOBALLE and KIMMEL, 1987). The conjunction of those mechanisms and the reduction of external nutrient loads (MARCE *et al.* 2006) favoured the replacement of harmful cyanobacteria populations by innocuous chlorophytes and diatoms in the epilimnion of Sau (JOAN ARMENGOL, unpublished data). In this sense, CARPENTER *et al*. (1992) suggested that if photosynthesis was restricted to a narrow mixed layer poor in nutrients, primary production would decrease by a factor of two to three.

Recently, many studies have revealed a marked increment in the heat content, ABHB, and water temperature of natural lakes (MORTSCH and QUINN, 1996; STEFFAN *et al*., 1998; AMBROSETTI and BARBANTI, 1999; AMBROSETTI and BARBANTI, 2001; BLENCKNER, 2005), and have also stressed the importance of these calculations to our understanding of potential response of aquatic ecosystems to climate change (EDMUNSON and MAZUMDER, 2002). Interestingly, our results demonstrated that the hydraulic management applied to Sau Reservoir induced a progressive temporal reduction on the average temperature and heat content in the reservoir, thus counteracting the generalized warming trend. This result has important implications. First, it highlights the fact that the effect of climate change on reservoirs with deep outlets could not be comparable to that in natural lakes. Thus, extrapolation of future scenarios tested in natural systems to reservoirs should be cautious. Second, our results pointed out that reservoirs with deep outlets could not be good sensor systems to detect limnological effects of climate change.

Our empirical and simulated results have demonstrated that the thermal dynamics of reservoirs submitted to selective withdrawal operations is essentially driven by the anthropogenic regulation of the stored water volume and the hydraulic operation of the outlet tower. Therefore, new scopes must be adopted to achieve appropriate empirical descriptions and numerical simulations of their heat dynamics. Additionally, this fact must be kept in mind for predicting the mixing depth and thermal characteristics in impoundments to be constructed.

Based in all the above-exposed observations, we have developed and validated a low-cost empirical model that enables water quality managers and aquatic ecologists to accurately describe and predict the impact of hydraulic strategies in the thermal characteristics of a man-made lake, using just inexpensive and easy-to-obtain hydraulic management information (water extraction depth and stored water volume). The model approach described here is applicable to support the evaluation of multilevel intake configurations for water supply reservoirs. From these results, similar models can be easily developed for specific reservoirs to support limnologically-based water quality management.

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FIGURE CAPTIONS

Figure 1. The annual development of the seasonal thermocline (expressed as temperature gradients) (A) for a selected set of years during the 1980-1985 period, when hypolimnetic withdrawal resulted in a deep thermocline and a wide metalimnion, and (B) for a selected set of years during the 1996-2003 period, when epilimnetic water flowed through the intermediate outlet inducing the development of a shallower thermocline. The solid black line depicts the daily evolution of the withdrawal depth.

Figure 2. The relationship between the water extraction depth (Z_{out}) and the mixed layer depth (Z_{mix}) in Sau Reservoir. Solid line represents Equation 5 in the text.

Figure 3. A) Monthly water volume recorded in Sau Reservoir during 1980-85 and 1995-2003 periods. B) Monthly heat content in Sau Reservoir during the studied period. Bold numbers in the top depict the ABHB (MJ m^{-2}). Black dots represent the simulated heat content values with Equations 6 to 9. R^2 and p values correspond to the observed-simulated data correlation.

Figure 4. A) Mean water temperature recorded in Sau Reservoir along the 1980-2003 period. B) Monthly average temperature in Sau Reservoir water column during the study period. Black dots represent the simulated temperature values with Equations 10 and 11. R^2 and p values correspond to the observed-simulated data correlation.

Figure 5. Mean monthly water column temperature for an average year of the 1980-2003 period. Continuous line represents the sinusoid function fitted for empirical modelling (Equation 7).

Figure 6. Relationship between measured T_{mean} and withdrawal depth in August ($Z_{out\ August}$). Solid line represents Equation 6 in the text.

Figure 7. Relationship between measured and simulated ABHB in Sau Reservoir. Solid line represents the 1:1 regression.

Figure 8. Model validation for A) water temperature, B) heat content, and C) ABHB

Figure 9. Temporal trend of the mixed layer depth (Z_{mix}, black dots) and the selective withdrawal depth (Z_{out}, solid line) in Sau Reservoir during the study period. The grey bold line depicts the hypothetic mixed layer depth if Sau behaved as a lake, computed from morphometric features following Patalas (1961).

TABLE CAPTIONS

Table 1. Sau Reservoir main morphometric, hydrological and water quality data. For some variables minimum and maximum values are given in brackets.

Table 2. Root Mean Square Errors (RMSE) computed for the model calibration and validation periods.

Figure 1

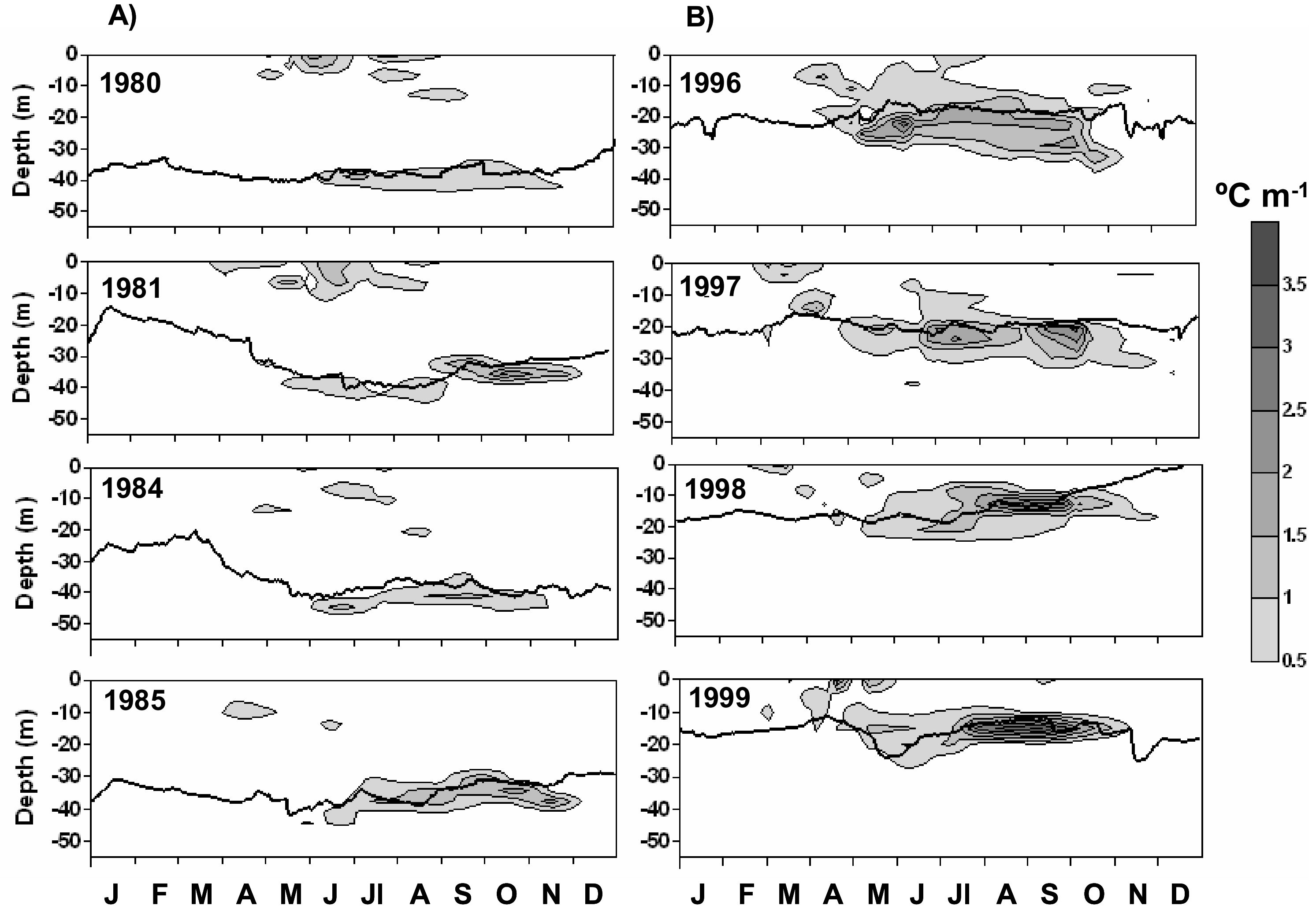
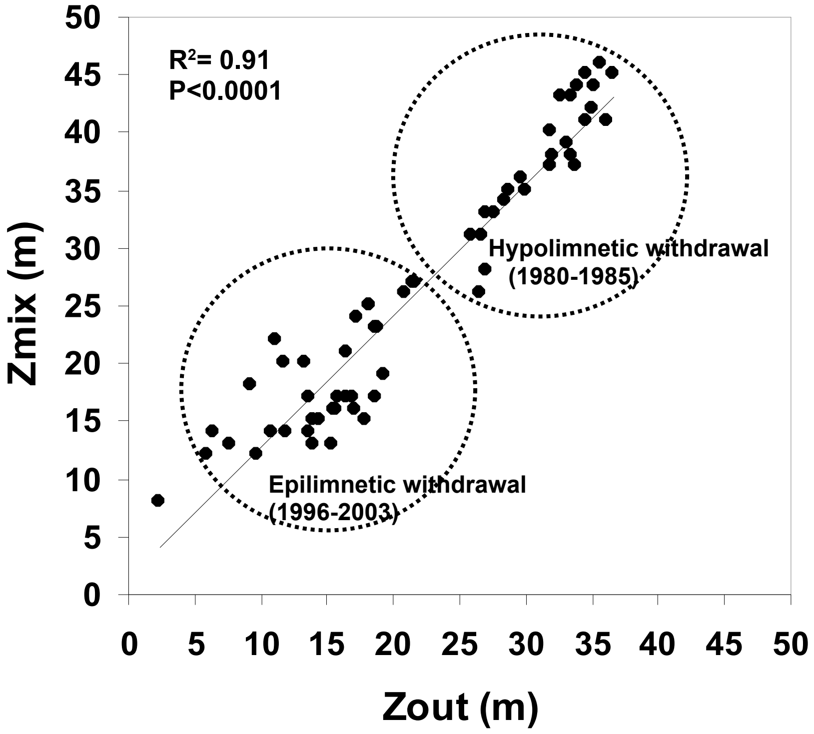
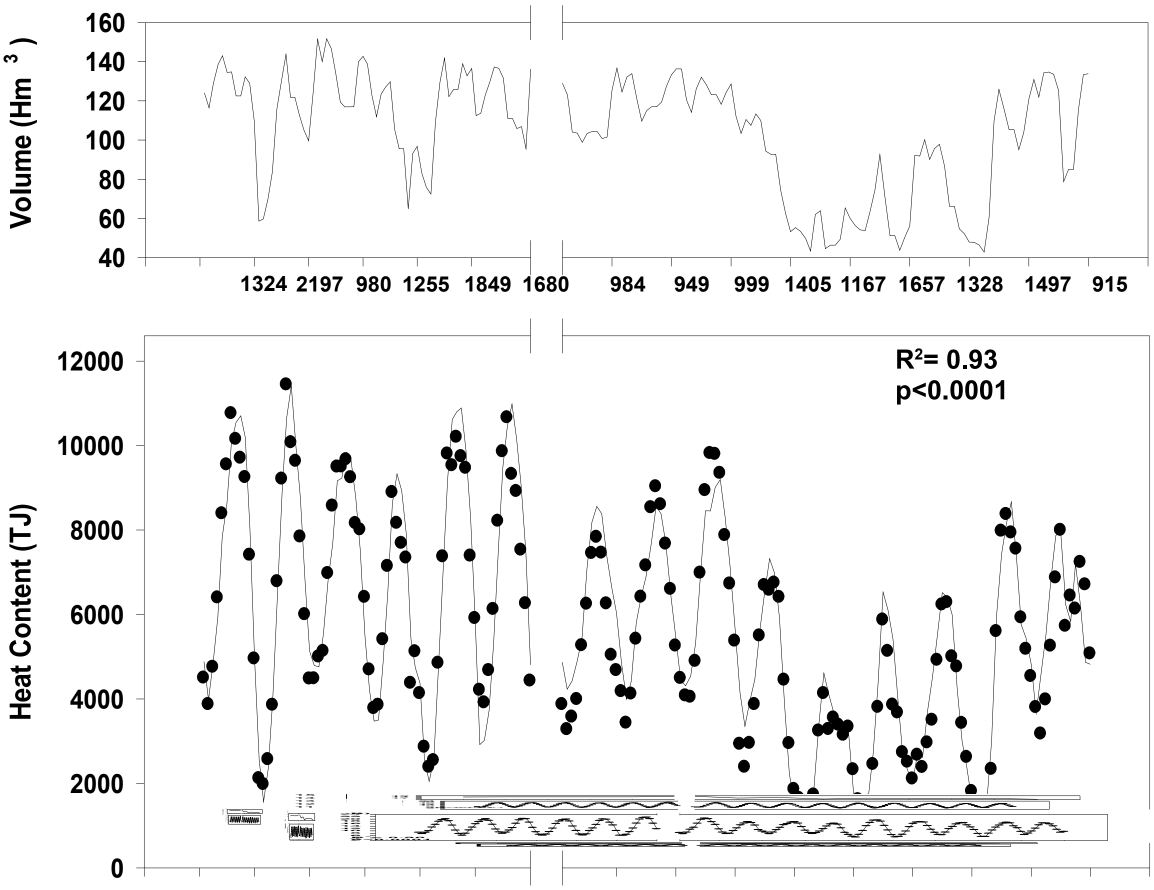

A)
B)
0
-10
-20
-30
-40
-50
Depth (m)
1980
1981
1984
1985
1996
1997
1998
1999
ºC m-1
3.5
3
2.5
2
1.5
1
0.5
J F M A M J Jl A S O N D
J F M A M J Jl A S O N D

Figure 2



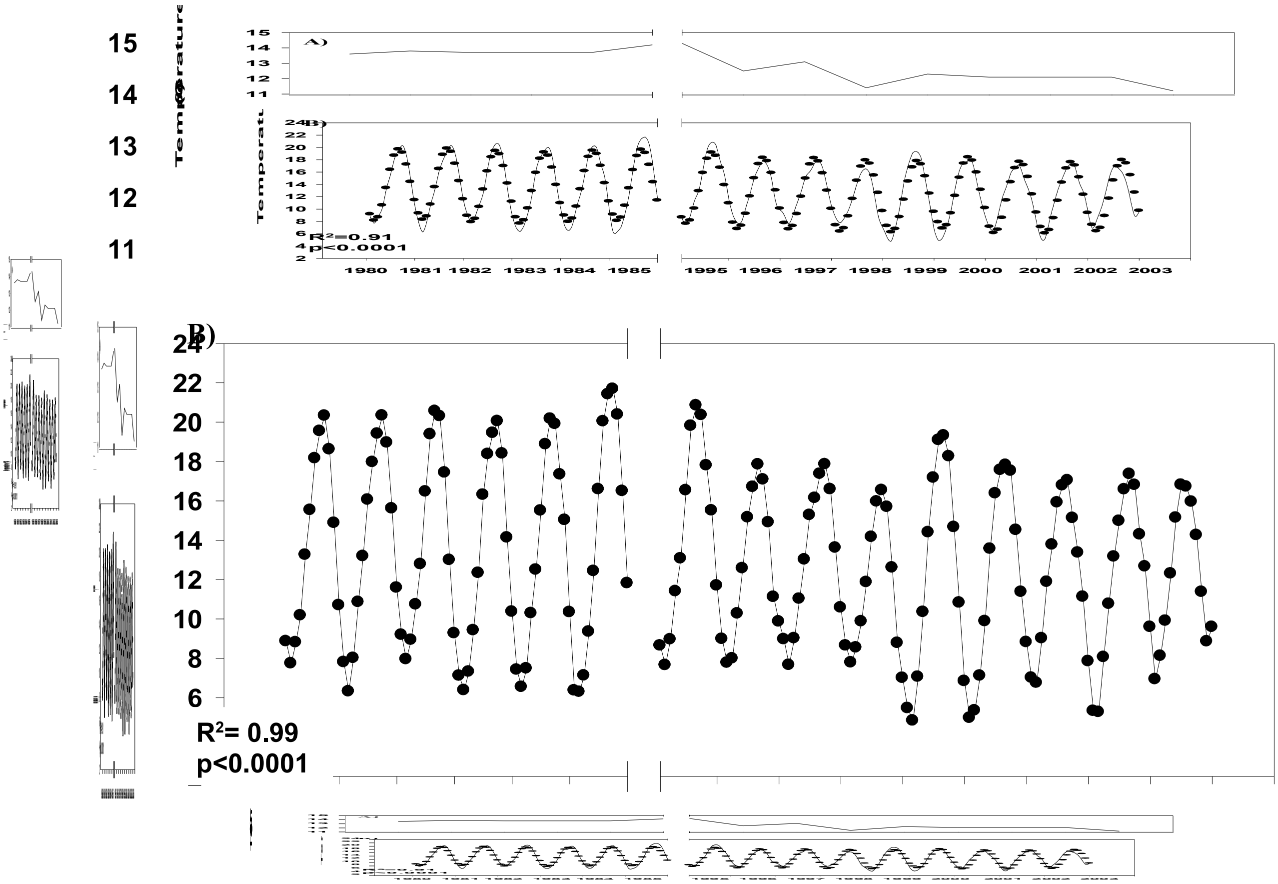
R² = 0.91
P<0.0001
Hypolimnetic withdrawal
(1980-1985)
Epilimnetic withdrawal
(1996-2003)
Zmix (m)
Zout (m)
0
5
10
15
20
25
30
35
40
45
50

Figure 3



Volume (Hm ^{3})
160
140
120
100
80
60
40
1324
2197
980
1255
1849
1680
984
949
999
1405
1167
1657
1328
1497
915
Heat Content (TJ)
12000
10000
8000
6000
4000
2000
0
R^2= 0.93
p<0.0001

Figure 4



A)
Temperature
15
14
13
12
11
B)
Temperature
24
22
20
18
16
14
12
10
8
6
4
2
R²=0.91
p<0.0001
1980
1981
1982
1983
1984
1985
1995
1996
1997
1998
1999
2000
2001
2002
2003
B)
24
22
20
18
16
14
12
10
8
6
R²= 0.99
p<0.0001

Figure 5

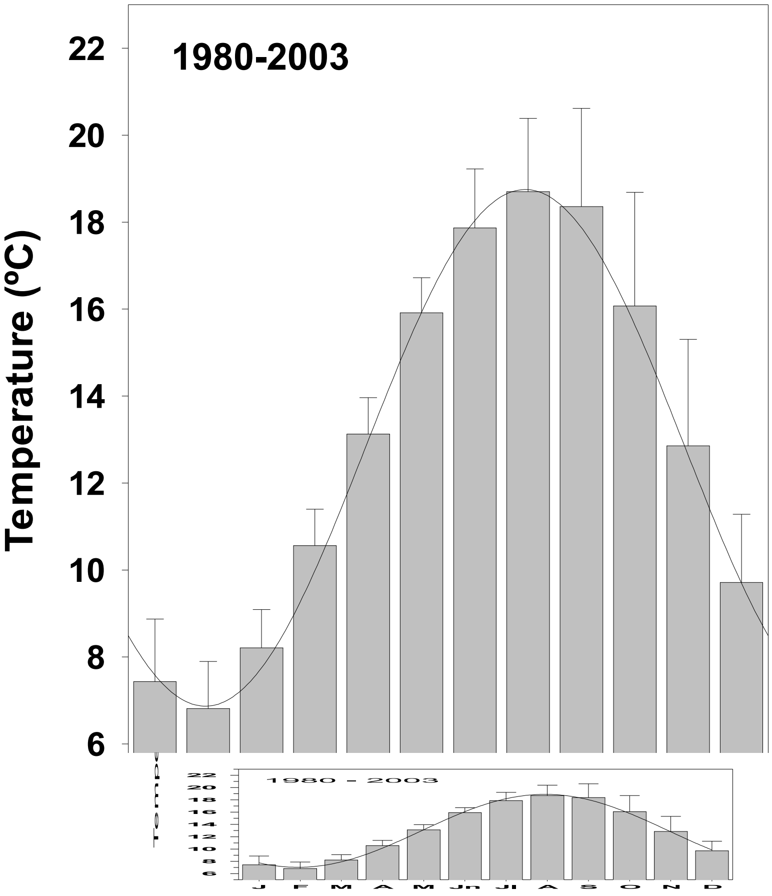

1980-2003
Temperature (ºC)
22
20
18
16
14
12
10
8
6
1980 - 2003
J
F
M
A
M
Jn
Jl
A
S
O
N
D

Figure 6

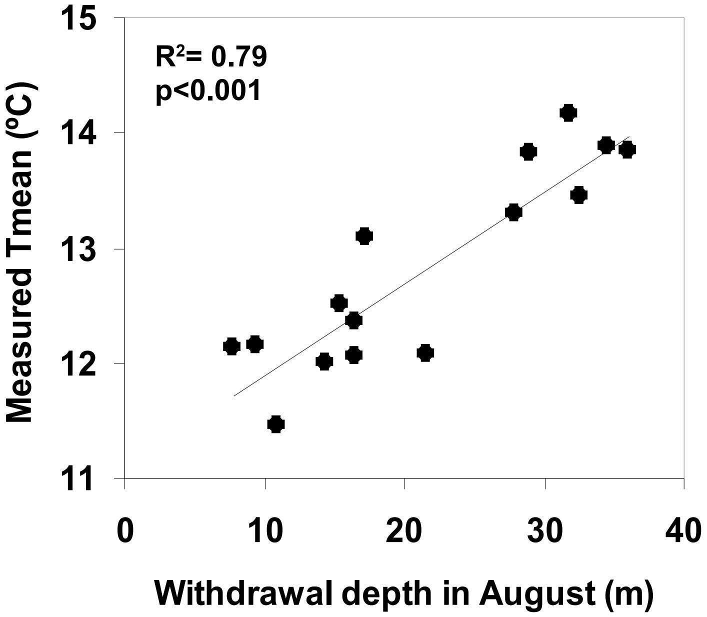
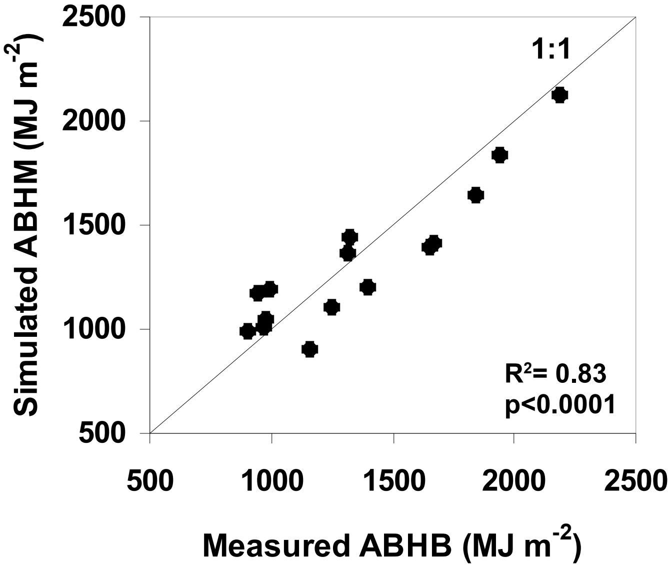

R²= 0.79
p<0.001
15
14
13
12
11
0
10
20
30
40
Measured Tmean (ºC)
Withdrawal depth in August (m)

Figure 7



2500
2000
1500
1000
500
Simulated ABHM (MJ m^{-2})
1:1
R^2= 0.83
p<0.0001
500
1000
1500
2000
2500
Measured ABHB (MJ m^{-2})

Figure 8

A

$R^2 = 0.95$
$p < 0.0001$

B

$R^2 = 0.95$
$p < 0.0001$

C

$R^2 = 0.75$
$p < 0.05$

Figure 9

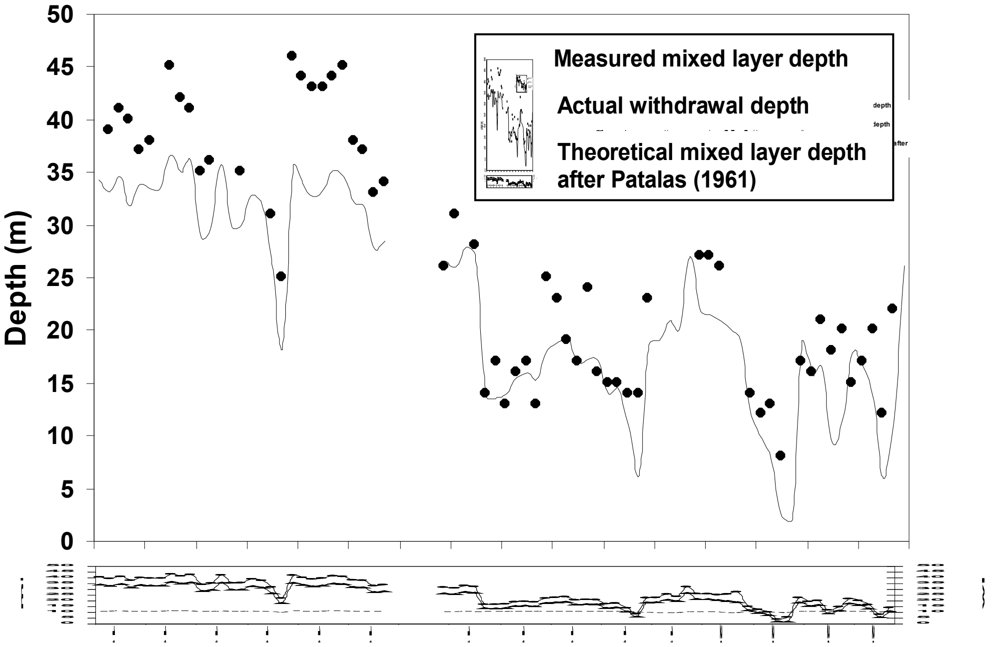

50
45
40
35
30
25
20
15
10
5
0
Depth (m)
Measured mixed layer depth
Actual withdrawal depth
Theoretical mixed layer depth
after Patalas (1961)

Table 1.

Variable	Value
Max. high above sea level (m)	424.54
Max. volume (x10^6 m^3)	168.5
Max. area (x10^6 m^2)	5.8
Max. depth (m)	65.0
Mean depth (m)	25.2
Max. length (x10^3 m)	18.0
Max. width (x10^3 m)	1.3
Mean inflow (x10^6 m^3 yr^{-1})	540.5
Mean residence time (yr)	0.3
Total Phosphorus (µmol L^{-1})	3.87 (0.29-28.31)
Total Nitrogen (µmol L^{-1})	202.4 (23.72-787.11)
Epilimnetic Chlorophyll-*a* (mg m^{-3})	14.60 (1.22-95.64)
Suspended solids (mg L^{-1})	8.03 (0.90-418.00)

Table 2.

RMSE Calibration			**RMSE Validation**		
Temperature (ºC)	Heat content (TJ)	ABHB (MJ m^{-2} yr^{-1})	Temperature (ºC)	Heat content (TJ)	ABHB (MJ m^{-2} yr^{-1})
1.43	706.28	175.50	0.97	976.51	253.36