Modelling of summer stratification of morphologically different lakes

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Abstract The use of a one-dimensional lake temperature model was investigated using long series of meteorological input data. These data were mainly based on one station. Effects of morphology on water temperature conditions were considered over this long period.

The studied lakes are from the Finnish Lake District. Concerning their dynamics, they are small with areas ranging from 257 km^2 to 0.14 km^2 with the largest depth about 80 m, but typically less than 50 m. The strength of thermal stratification varies. Verification was made using test summers: for two larger lakes longer periods could be used. Summer stratification periods could finally be resolved satisfactorily, but only after adjusting with data from each lake. For some years the vertical temperature simulations are not as successful as for others, indicating the importance of local weather differences.

For lakes with a large area to depth ratio heat is absorbed freely, while when it is small heat is blocked more into the epilimnion. For very small lakes sheltering is essential. Large total volume delays cooling, when stratification prevails. Sheltering is important and also very small lakes cool slowly due to their strong stability.

Keywords Lake stratification; lake temperature model

Introduction

The study of lakes and their thermometric have often included intensive empirical tests on-site, but theoretical models have also been developed. However, due to the complexity of nature empirical results and models are typically limited and their results cannot simply be generalised to different conditions in space and time. Numerically solvable physical models with mathematically described processes give better bases for this. Again, due to the complexity it is often difficult to develop a model which is complex enough to give accurate enough results but not too complex so that its use is not too slow and difficult. New methods and larger computer capacities have given new possibilities for solving involved complex computational problems with the necessary detailed data. This has enabled us to study questions related to, for example, environmental changes in a new way by using physically based models with mathematical formulations, which give verifiable numerical solutions. The approach can also unite and verify old knowledge, which otherwise cannot be done. With long data series it is possible to obtain enough information to assess the results and suitability for different kinds of lakes found in nature. With more precise mathematical descriptions, the results can be defined with clear limits and assumptions. Processes in nature can be related to the definite numerical model output.

When a model is constructed all the processes occurring are analysed, together with the associated scales and causal relations, remembering the required resolving capability. In lakes physical processes very often dominate, e.g. temperature often regulates biological processes. Highly detailed models require many adjustments, and usually climate models can be connected with lake models only for lakes for which enough empirical adjustment data can be found. Even a simple one-dimensional model usually needs a lot of adjustment, and when more details are wanted to be solved adjusting becomes more demanding. Long data series include large variations in meteorological conditions, which gives the possibility to study the output range. The suitability of the models for different lakes and conditions can be tested and fine-tuned, also taking important local features into account. This improves the reliability and generality of the models and makes them more broadly applicable.

The most important morphological features affecting thermal conditions of lakes are depth and area, but also the shape of the lake is important. The shape of the lake and the surrounding landscape form a meteorological field over the lake and accordingly areal exchange through the water surface area. This affects how heat is transferred and distributed within the water column. For larger lakes the importance is smaller, because shore regions are relatively smaller. Depth and shape of the lake basin below the water surface affect how heat is transferred. In Finnish conditions the summer vertical water temperature profile is typically stratified, divided into a warmer surface layer epilimnion and cooler hypolimnion. Formation of stratification is found to be so important that it has been used in the classification of lakes. Over larger scales climate conditions vary over the globe and thermal conditions of lakes vary accordingly: when heating is sufficient stratification is formed and maintained throughout the summer, but close to the equator it can be broken several times during summer, when the hypolimnion is also heated sufficiently. When the temperature difference between the layers is small, it is more probable that wind is strong enough for a long enough time to mix the water. In Finnish conditions this seldom occurs during summer and typically only in lakes which are relatively open. Strong throughflow also increases the probability of overturn. Stratification is critical also when modelling is concerned: the model should be able to describe it and also the temperature in various conditions and lakes.

Also the origin of lakes and the formation of the landscape vary from place to place. Hutchinson (1957), who described the differences of lakes regarding stratification, connected the geographical division of land and water with the formation of the Earth's surface, including lakes. Burgis and Morris (1987) discuss lake districts and their formation. The lakes in the Finnish Lake District came into being on the moraines, which explains much of their morphological features. They are close to each other, they have complicated shapes and, typically, shallow shore areas are large. Their maximum depths are less than 100 m, often less than 50 m and the average depth is 7 m. The landscape is also relatively flat and there are no high hills. The climatic conditions in Finland, with its large number of lakes, have recently been discussed in a meteorological context by Vihma (1995), Venäläinen (1998) and Tuomenvirta (2004). Information about Nordic conditions is also available from reports edited by Thendrup (1985) and Virta (1986). Operative watershed models are being used extensively to calculate hydrological elements: they also use meteorological data for input. Evaporation is an important component of these models, especially in an area with many lakes. Anyhow, hydrological models usually include rather simple descriptions for lakes and it would be beneficial to be able to unite hydrological models and lake models. Some attempts have been made to include calculations of the surface water temperature of lakes in an operative hydrological watershed model (Elo and Koistinen 2002). In that study the lake model was simply a box, but for lake studies more complicated models are needed to resolve temperature profile in water.

The lake model in this study is a kε-model, the PROBE model (Svensson 1978). It had earlier been tested for Lake Pääjärvi for computing all the energy balance components (also evaporation can be calculated) (Elo 1994) and its sensitivity to changing climate was studied with the SILMU scenarios in the study of the Finnish Research Programme of Climate Change (Elo *et al.* 1998). In this and a preceding study (Huttula *et al.* 1992) model versions were used to study some other lakes in Finland with different versions of scenarios. The ice model section has been compared with those used for Lake Mendota (WI, USA) and the LIMNOS ice model (Elo and Vavrus 2000). This paper describes how the model can be used for a variety of lakes in a lake district, applying it as systematically as possible and the results are analysed.

Material and methods

The model system used in this study considered the atmosphere, lake water and ice coverage as main components. Meteorological data were modified, taking into account all the necessary averaging. Usually, accurate lake models require actual lake data and this was also the case here. However, data provided by synoptic stations are used as well. Various methods have been developed to adjust synoptic systems and lake model systems, depending on the individual characteristics of any given lake. Lake researchers can then obtain the desired model output meeting their demands and use the climate modeller's recommendations effectively.

The optical properties of water can change during summer, often due to strong algal blooms. Light extinction was considered in the calibration: in some cases it had importance, but changes were not needed for the lakes considered. Typically the waters in the area are very dark and light can penetrate only the uppermost layers, typically 2 m.

Stratification was solved from calculated profiles with a program by Professor Juhani Virta. Stratification was determined to exist with certain criteria: large enough temperature differences between epi- and hypolimnion. A spline was fitted to a vertical temperature profile and the point with the largest change was chosen as the location of the thermocline. This kind of point can be found at different depths, but on average it represents the thermocline depth. The length of the stratified season was defined as the continuous period with a thermocline. For lakes with stable stratification this can last continuously over summer. However, for lakes with more irregular behaviour destratification could occur followed by a typically longer stratified period. On these occasions this later period was determined as the stratified period: typically the total duration of stratification was then short. The stratified period was assumed to be between the beginning of May and the end of October.

Lake data

Measurements of small, shallow lakes are usually taken as part of special study programmes and they are not recorded in the registers of the Finnish Environment Institute (SYKE) (Korhonen 2002). Some information can be found in a study by Kuusisto (1981). Research on small lakes (typically less than 0.5 km^2) done at Evo near Lake Pääjärvi had been published by Arvola (1986). The research station at Evo was founded in 1892 by Oskar Nordqvist (Rask *et al.* 1992), who is regarded as the first to have undertaken physical lake research in Finland (Simojoki 1978). Nordqvist began to make temperature observations in large lakes in the Finnish Lake District in 1883. He also conducted studies in the Baltic Sea and Lake Ladoga (Simojoki 1978). Another Finnish lake scientist, Heikki Järnefelt, also conducted numerous studies on small lakes (Eloranta 1992). For the area, it is typical that the lakes stay stratified during summer, but there are exceptions. Lake Pyhäjärvi, with a rather large surface area of 154 km^2 and a mean depth of only 5.4 m, is a good example of a shallow lake with polymictic behaviour (Virta and Elo 1994). The shape of the basin can also favour polymictisism. Destratification has been observed in the bowl-shaped Lake Lappajärvi (Odenwall 1934), although its mean depth is close to the average in Finland, about 7 m. Surface area is close to 150 km^2. Lake Lappajärvi is thought to have been created as a result of a meteorite impact (Hjelt 2001).

Six lakes with different morphology and size were selected (Table 1, Fig. 1). The values of the greatest depths have been obtained so that they should adequately describe the basins

Table 1 The study lakes

Lake	Area (km^2)	Max. depth (m)	Wind factor	Location
Lake Pääjärvi	13	85	1.17	61°04′N, 25°08′E
Lake Valkea-Musta	0.14	10.5	0.6	61°13′N, 25°07′E
Lake Kallavesi	887	71		62°50′N, 27°40′E
-sub-basin	41	50	1.1	
Lake Jääsjärvi	65	20	1.3	61°37′N, 26°08′E
Lake Vanajanselkä	109	24	1.5	61°10′N, 24°10′E
Lake Näsijärvi	257	51	1.13	61°32′N, 23°45′E

considered. From Lake Kallavesi only a sub-basin was selected. Lake Vanajanselkä is the main basin of Lake Vanajanvesi (the middle part, which is rather clearly limited by the sounds connecting the sub-basins). These lakes have been involved in many lake study projects: in particular, currents and mixing have been studied. Meteorological data were mainly from the cities Jyväskylä and Helsinki (Fig. 1). Fig. 2 presents the hypsographic curves of the lakes: the depth from the surface is on the y axis, while the corresponding areas

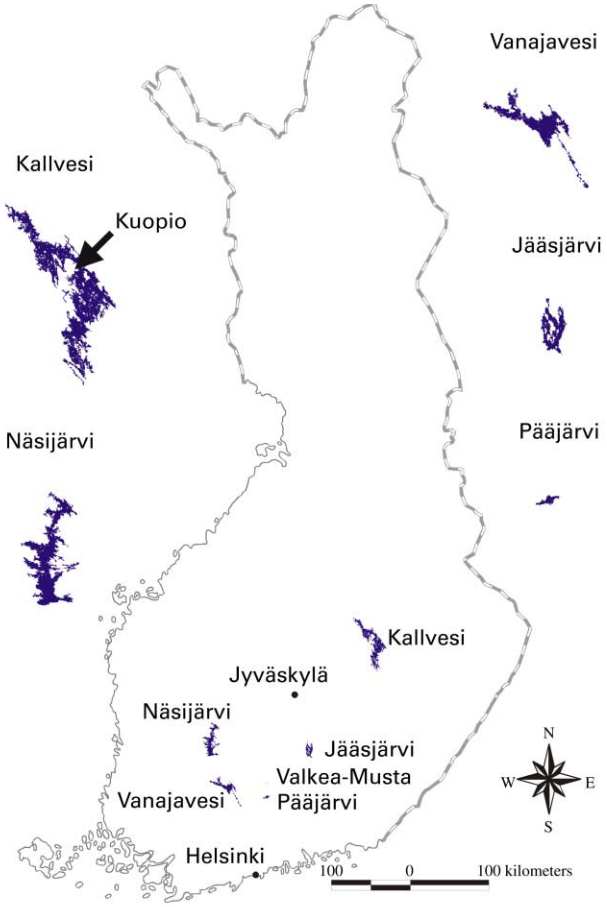

Figure 1 The study lakes. The six study lakes and their locations are shown on the map of Finland. Lake Valkea-Musta is so small (although enlarged) that it is hard to see. The shapes of the other lakes are enlargened and shown next to the map to show their shapes. (©Maanmittauslaitos, lupa nro 468/MYY/04)

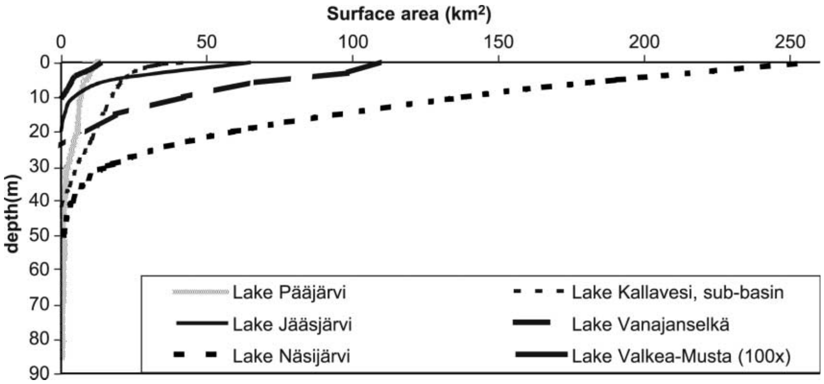

Figure 2 Hypsography of the study lakes. The curves of the area versus depth for the study lakes are drawn to the same scale, except for the small Lake Valkea-Musta, which is drawn with its area multiplied by 100

of each depth are given on the *x* axis. In the figure the values of the area of the small Lake Valkea-Musta are multiplied by 100 to make it visible for comparison with the others.

Usually the water temperature observations made in long term monitoring in Finland over decades have been made infrequently, only two to five profiles in a month. It is recognised that more frequent observations would provide better data for representing average values. Lakes Kallavesi (data from SYKE) and Näsijärvi (data from Pirkanmaa Regional Environment Centre) are rare lakes in Finland: temperature soundings over several years over the study period were available. The verification of the calculation results were mainly made using daily averages from corresponding depths. The observations are made during daytime, usually in the afternoon. This may add a certain bias when daytime heating is present in the top layers. For the smaller lakes, data were from studies of the Department of Geophysics, University of Helsinki, especially by Professors Palosuo and Virta. They have also gathered the data used in this study (Lake Vanajanselkä by Palosuo and Lakes Jääsjärvi and Valkea-Musta by Virta). These data included frequent temperature profile recordings for some years, but for Lake Vanajanselkä individual soundings had to be used.

Meteorological data

The data used here are from the central part of the Finnish Lake District, from Jyväskylä. The series cannot be regarded as first class (e.g. Schönwiese and Rapp 1997) but it was possible to make comparisons, evaluate results and make corrections correspondingly. For this study only a part of the data were selected: the period with automatic weather station recordings for the period 1950–1997 (the year 1953 is missing). The older meteorological data (1916–1949) included wind direction and speed obtained by visually estimating the position of a wind vane, which increases the possibility for, for example, selective bias. The proper treatment of that would have demanded too much work (and been not so reliable) to obtain proper mixing in water, which is very sensitive to wind changes. Calculations were made using all of the available data to check the numerical stability over the whole period. The problems concerning winter ice cover are different and not so sensitive to wind changes. The results obtained with the older data were not much worse than with the newer data. Those results are going to be discussed in a future paper using the entire data series (Elo 2005).

The summer season results are given from 1951. After 1950 data were recorded at Jyväskylä Airport. Only minor microclimatic changes have occurred at that site over those 46 years. As a result, the data from the airport can be assumed to be rather homogenous. The airport, as an open area, displays meteorological conditions similar to those of a lake.

This concerns roughness, but many features concerning temperature, moisture and heat are different over land than over water. The weather systems travel over the area relatively unchanged. It is not possible to estimate all the short-term fluctuations that can occur. Locally important differences can be caused also by, for example, landscape.

The most important regional variations over the area were taken into account, comparing weather station data over Southern Finland and using their earlier studies, for example by Heino (1994). It is possible to see differences that can be understood using geography relating the changes according to landscape and location to the physical conditions. The temperature of air in Jyväskylä were compared to several stations around it. The most important input for the model is the correct level of wind speed. That is influenced by the observation method and recording height, which are affected also by the surroundings of the site and changes occurring in it. Winds have large variability, which strongly affect open water calculations, and it was found necessary to modify wind in calibrations for each lake. Wind direction is very important for many phenomena, but for these applications it was applied directly as recorded in Jyväskylä. Cloudiness was used in the calculation of long and short wave radiation. It was compared between Pääjärvi and Jyväskylä, and an average level of modification could be made. Short wave radiation measurements by the Finnish Meteorological Institute were used and a factor was determined as a function of latitude, making comparisons with the earlier model for Lake Pääjärvi. Relative humidity observed at Jyväskylä was rather similar to what was determined for Lake Pääjärvi, although over the land area it was slightly drier and variations were larger. It was not modified for its use as an input but diurnal variations and differences from actual lake data turned out to be very important for the model.

The PROBE model

The lake model uses the PROBE program, which is an equation solver for vertically one-dimensional, transient boundary layers, which solves equations of the form

$$\frac{\partial \Phi}{\partial t} = \frac{\partial}{\partial z}\left(\Gamma_{\Phi}\frac{\partial \Phi}{\partial z}\right) + S_{\Phi}, \tag{1}$$

where Φ is a dependent variable, t is time, z is the vertical coordinate, Γ_{Φ} is the exchange coefficient and S_{Φ} is the source or sink term. The lake is described according to the hypsography, the area–depth curve as a pile of boxes, each with its height , Δh_i with the largest on top having the surface area. For each time step all the wanted equations are solved over the vertical, giving suitable placing for Eq. (1), first solving for temperature and horizontal velocities. For the heat energy it can be written

$$\frac{\partial}{\partial t}(\rho c_p T) = \frac{\partial}{\partial z}\left(\frac{\mu_{\mathrm{eff}}}{\rho\sigma_{\mathrm{eff}}}\frac{\partial}{\partial z}(\rho c_p T)\right) + S_l, \tag{2}$$

where c_p is the specific heat at constant pressure, ρ is the density T and is the temperature. Water is heated by short wave radiation, which is absorbed in the water column. μ is the dynamical viscosity and σ the so-called Prandtl–Schmidt number. The subscript refers to the effective value, which is the sum of the laminar and turbulent parts. The source term $\mathrm{S_l}$ describes absorption of short wave radiation. It can be described by an exponential bulk form $(1-\eta)e^{-\beta z}$, where η is the fraction absorbed at the surface and β is the light extinction coefficient.

In the process of solving the boundary exchange is calculated. At the surface wind velocity is used. Typically currents in the lakes are induced by wind and formed by the basin. They are described with horizontal velocity components, which can be interpreted as characteristic, as the model is actually one-dimensional and horizontality is represented with isothermal layers. The effect of rotation of the Earth is included in the Navier–Stokes equations, which are used to solve horizontal velocity components. The current velocity is turned slightly from the wind velocity at the top and spirally downward (the so-called Ekman spiral, when the wind is stationary). This is a simplified picture for one-dimensional treatment and again assumes no horizontal boundaries. Naturally, the current field is more complicated and local differences exist. Rotation of the Earth also causes internal rotating waves along the basin. When the lake is large enough for such waves they can be seen. This is often used for classifying lakes according to their sizes. The lakes and their main basins in this study are rather small and these waves were not expected to be large enough to add effects to the thermal development. Also the broken shape of the shores damp the propagation of those waves. As the dynamics in the atmosphere is also influenced by the Earth's rotation such effects can often be seen in the current spectra. The important forms of internal waves are longitudinal standing waves; wind can induce them in the stratified two-layered water. Their effect can be incorporated into the model's horizontal velocity components. The waves and their interaction with the bottom can influence mixing, especially when the bottom topography is such that the thermocline can sweep the bottom. Over the vertical, gravity is important.

Turbulent kinetic energy k and its dissipation rate ε are solved with corresponding placements into Eq. (1). A $k\varepsilon$ model is needed for a II-order closure of the equations: the dynamical turbulent eddy viscosity μ_T is calculated as $\mu_T = C_\mu \rho k^2/\varepsilon$, where C_μ is an empirical constant. The constants used by the turbulence model are summarized by Omstedt *et al.* (1994). For deep lakes the so-called deep-mixing routine has sometimes been successfully applied (e.g. for the Baltic Sea by Stigebrand (1987)). It was used in earlier applications for Lake Pääjärvi, so no more empirical adjustment for mixing in water was needed (Elo 1994; Elo *et al.* 1998). With deep mixing, the term $-\rho_{\mathrm{ref}} A_s/N$ is added to turbulent viscosity. In it, ρ_{ref} is the reference density 999.975 kg/m^3, A_s is a constant, 2×10^{-7}, and $N = \sqrt{-(g\Delta\rho)/(\rho\Delta z)}$ is the Brunt–Väisälä frequency. g is the normal acceleration by gravity. Generally, for deep waters density effects are of more importance and with greater depths (more than 100 m) they should be studied more carefully.

The flux of heat through the surface, in addition to the radiation absorbed, is given as a sum $F_E + F_H + F_L$, where F_E is the flux of latent heat, F_H is the flux of sensible heat and F_L is the net long wave radiation. In the model fluxes are given $-F_E = F_E(T_a, RH, u)$, $F_H = F_H(T_a, u)$ and $F_L = F_L(T_a, RH, Cl)$ – as functions of the measured input they need: T_a is the temperature of air, RH is relative humidity, u is wind velocity and Cl cloudiness. Global radiation for the source term was calculated using location and cloudiness. The calculated surface temperature was used to determine thermal long wave radiation emitted from water. The rate of change of the heat storage of the lake Q was approximated with the calculated temperature profiles. The heat balance equation per unit surface area of the lake can be written as the sum $F_L + F_H + F_E + Q = \delta$, where δ is a (possible) residual. When it is calculated using the PROBE lake model, it is balanced to be practically zero.

The vertical fluxes of momentum, τ, sensible energy, H, and water vapour, E, are given by the equations

$$\tau \approx \rho_a K_M \frac{\partial u}{\partial z} = \rho_a C_{Dz} u_z^2, \tag{3}$$

$$H \approx -\rho_a c_p K_H \frac{\partial T}{\partial z} = \rho_a c_p C_{Hz}(T_s - T_z) u_z, \tag{4}$$

$$E \approx -\rho_a K_E \frac{\partial q}{\partial z} = \rho_a C_{Ez}(q_s - q_z) u_z, \tag{5}$$

where u is the wind velocity, T is the temperature, q is the specific humidity, ρ_a is the density of air and c_p is the specific heat capacity of air. The water surface (subscript s in the formulae) and the height z along the vertical (subscript z) are chosen here. K and C, with their subscripts, are the corresponding bulk exchange coefficients, where the latter form is used. The wind stress in Eq. (3) is calculated with $\rho_a C_{Dz} = 1.69 \times 10^{-3}$. Equations (4) and (5) are treated according to the formulation presented by Friehe and Schmitt (1976). $C_{Hz} = C_l + C_H$ is determined with stability, the product of wind speed and the temperature difference: when that is less than zero, the situation is stable and $C_l = 0.0026$ and $C_H = 0.00086$. When the product is positive, but less than 25°C m/s, the situation is unstable and $C_l = 0.002$ and $C_H = 0.00097$. Otherwise, the situation is very unstable and $C_l = 0.0$ and $C_H = 0.00146$. The parameter $C_{Ez} = 1.36 C_H$ and the moisture difference is given in water vapour pressures, while fluxes are in W/m^2. The reference height is 10 m. The actual surface temperature should be the so-called skin temperature but, according to the original article, the measured temperature at 1 m depth was often used. These parameters were the same for each lake, but an additional factor was used in the calibration to multiply wind as described in the next subsection (factors included in Table 1).

Model adjusting and calculations for the lakes

The model applications were based on earlier models for Lake Pääjärvi. The lake had been studied in many projects and the PROBE model had earlier been adjusted for it and its sensitivity had been estimated. Actual lake data were originally used, then later synoptic data and climate change data (Elo 1994; Elo *et al.* 1998). In those studies synoptic temperature and moisture of the air were modified to correspond to the conditions over the lake. These modifications were not made to these data because micrometeorological conditions over different lakes can differ from each other and synoptical data were wanted to be adjusted to overcome these problems. For Lake Pääjärvi the deep mixing routine used earlier did not apply any longer. This is an important example, showing that it is not always possible to separate the treatment of surface input data and routines and the model of water mixing, since the surface input has very important effects on the results of the water temperature profile. Describing the turbulent exchange always includes simplifications, which can influence even what kind of lake water model should be used.

Lake Valkea-Musta was studied as an example of small lakes. The number of small lakes in Finland is remarkable: almost all lakes (99%) in Finland are smaller than 1 km^2. Small lakes are easily affected due to their small water volume and sheltered conditions. Sheltering decreases wind and often the through flow is also small. Stratification can be very stable when motions, which could smooth large temperature differences between epi- and hypolimnion, are slow. In Finland this is intensified by turbidity and darkness of the water. For small lakes direct insolation can be relatively strongly reduced, even when the terrain has no high obstacles. For adjusting the model for Lake Valkea-Musta short wave radiation was also reduced using lake measurements from the calibration year 1980. It also improved results concerning the calculation of ice break-up, which also supported the reduction. In nature water in this kind of small lake can start to warm early before ice melts, which speeds up the ice break-up. Also sheltering from winds increases the temperature of the air over a small lake.

Lake Kallavesi is the fifth largest lake in Finland. It has many sub-basins with considerable and varying depths. It turned out that it was not possible to apply the model as a whole for the entire lake, so the main basin was selected for analysis. It is located to the southeast from the town Kuopio (Fig. 1). The sub-basin site has been used as an observation site for ice observations and temperature soundings. It was possible to adjust the deep mixing routine for this sub-basin. Verification of the temperature simulations were done using profile data from 32 summers from 1964–1997.

Lake Jääsjärvi has a very complicated shape. The thermistor chain data used for adjusting were from the main basin, the hypsography of which resembles that of the whole lake. The complicated shape increases local variations of the meteorological field, complicating the suitability of a one-dimensional model. The temperature close to the bottom, and particularly to the surface, is still more easily solved even with these data: however, the middle layer and thermocline are more problematic. For the calibration years calculated results for Lake Jääsjärvi were occasionally not as successful as usual, indicating that there can be local variations which, in some instances, have more importance.

Lake Vanajanselkä also has a complicated shape. It does not stratify as strongly as the other lakes and there can be overturns during summer. The temperature difference between epi- and hypolimnion can be only about 2°C in that lake, when it is more usually 6–10°C during warmer periods. The modelled temperature structure is strongly influenced by modifications of the air temperature, wind speed and extinction coefficient, but it was possible to find a combination such that the main features were rather well modelled. Generally the temperature range was rather well solved, although there were differences between the instantaneous calculated and measured temperature profiles.

Lake Näsijärvi also has many basins with complicated shapes, so the main division is into three basins. Sub-basins of the lakes in the area are often perpendicular to each other due to geological processes forming the landscape, the lakes in Finland often having such crossing basins. These affect, for example, internal waves: broken complicated shores can also prevent forming of standing waves, whereas in regular deep basins they are easily formed. Also for Lake Näsijärvi the percentual hypsography (areas in percent relative to surface area) is rather similar for the whole lake and the south sub-basin, where the temperature observations were conducted. There were temperature profile observations from 1970–2000.

Numerical problems can arise when very small differences are calculated along the vertical. This can lead to situations close to dividing with zero. Up to 100 grid cells are available and it is advised to use a finer grid for the top layers and at the thermocline depth. Still, problems can occur, especially when deeper lakes are calculated. This can lead to a temperature of zero in the middle depth, for example, which leads to freezing even at the end of summer, which is totally unrealistic. These occasions can be affected even with small changes in the parameter values used, and the easiest way to correct the situation is to use slightly different values for the problematic situation. This is usually enough to avoid the relatively rare extra small differences. The parameter value can be retained until after the situation has been passed, and the obtained change in the results is very small and lasts only for a short time. Usually the problem can be corrected, increasing the numerical precision used in the calculation, but that can lead to several times longer calculation times. That can also be used in checking the results. In some cases the result can drift due to too small precision, but usually numerical problems produce clearly erroneous results. It is anyway important to check the results.

Results and discussion

Fig. 3 shows examples of the results obtained in 1982 for Lakes Valkea-Musta and Jääsjärvi. Both lakes were first stratified in spring, but surface water had then cooled and overturn had occurred for Lake Jääsjärvi. The smaller Lake Valkea-Musta is more sheltered and only surface layers have been mixed at about the same time. It has warmer water at the surface, but after its overturn Lake Jääsjärvi has considerably warmer water in its hypolimnion. The model was able to describe these features well.

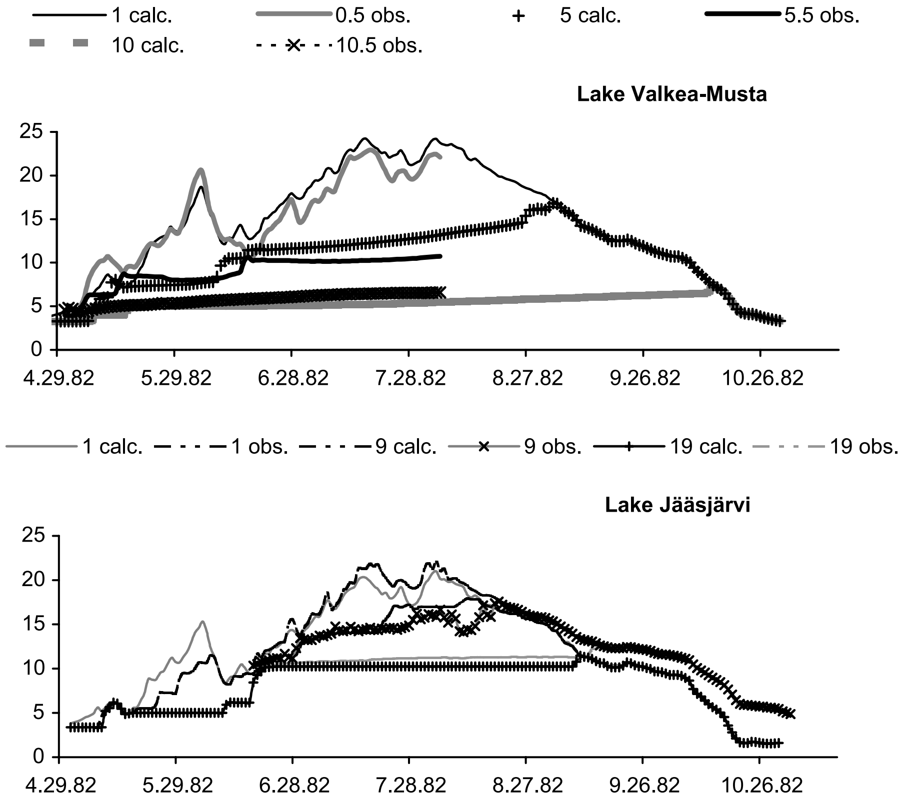

Figure 3 Temperature development in Lakes Valkea-Musta and Jääsjärvi in the year 1982. Both of the lakes have stratified. In Lake Jääsjärvi overturn has occurred in June, but in Lake Valkea-Musta only the surface layers have mixed. Available observations (drawn in the figure) support this

Statistics of the calculated stratification periods are given in Tables 2–4. Overturn can shorten the period for Lakes Jääsjärvi and Vanajanselkä. According to calculations the mean stratified period is shortest for Lake Vanajanselkä, beginning in June and lasting for 105 days. For Lake Jääsjärvi the stratification is the second shortest: 124 days. It begins rather late, on 19 May and ends early on 19 September. In the small sheltered Lake Valkea-Musta stratification starts typically already at the beginning of May. The rest of the lakes are larger and deeper and they stratify later: Lake Pääjärvi with a rather small surface area on 14 May, with the rest on 21–23 May. In Lakes Vanajanselkä and Jääsjärvi overturn typically occurs

Table 2 Calculated stratification for the study lakes. The dates are given for the determined average beginning and end of the continuous stratification period, together with the corresponding depth of the thermocline and its calculated temperature*

Lake	Beginning	Thermocline depth (m)	Temperature (°C)	End	Duration
Valkea-Musta	May 6 (8)	4.7 (0.3)	13.4 (0.9)	Oct. 13 (8)	161 (11)
Jääsjärvi	May 19 (14)	9.9 (1.2)	11.7 (1.6)	Sep. 19 (11)	124 (20)
Vanajanselkä	June 2 (15)	12.3 (2.6)	12.4 (1.8)	Sep. 13 (11)	105 (23)
Näsijärvi	May 23 (8)	14.7 (1.3)	11.1 (0.8)	Oct. 20 (9)	150 (13)
Kallavesi	May 22 (7)	10.3 (1.3)	12.5 (0.5)	Oct. 12 (6)	142 (10)
Pääjärvi	May 14 (7)	11.3 (1.6)	10.9 (0.9)	Oct. 27 (6)	164 (11)

[*] Bracketed values represent standard deviations

Table 3a Maximum and minimum for the start and end dates of the lake thermal stratification as calculated with the lake model

Lake	Earliest start date	Earliest end date	Latest start date	Latest end date
Valkea-Musta	18 Apr. 1990	23 Sept. 1973	27 May 1955	26 Oct. 1961
Jääsjärvi	1 May 1974	22 Aug. 1981	22 Jun. 1981	11 Oct. 1962
Vanajanselkä	4 May 1993	3 Jun. 1955	24 Jul. 1983	21 Aug. 1983
Näsijärvi	8 May 1993	5 Oct. 1966	9 Jun. 1951	31 Oct. 1996
Kallavesi	9 May 1993	30 Sept. 1973	4 Jun. 1951	24 Oct. 1951
Pääjärvi	1 May 1989, 1990	6 Oct. 1977	31 May 1955	31 Oct. 1964, 1996

Table 3b Longest and shortest duration of thermal stratification as calculated with the lake model*

Lake	Longest duration	Shortest duration
Valkea-Musta	26 Apr. – 23 Oct. 1991 (180)	21 May – 29 Sept. 1952 (131)
Jääsjärvi	8 May – 11 Oct. 1983 (156)	22 Jul. – 26 Aug. 1981 (65)
Vanajanselkä	15 May – 28 Sept. 1963 (136)	24 Jul. – 21 Aug. 1983 (28)
Näsijärvi	10 May – 31 Oct. 1990 (174)	3 Jun. – 6 Oct.1977 (125)
Kallavesi	15 May – 23 Oct. 1961 (161)	1 Jun. – 2 Oct. 1977 (123)
Pääjärvi	1 May – 31 Oct. 1989 (183)	30 May – 6 Oct. 1977 (129)

*Bracketed values represent the duration in days

already on 13 and 19 September. The deep Lake Pääjärvi has overturn late at the end of October (in some cases it could occur even later). In Lake Näsijärvi stratification lasts longer due to its large heat storage, until 20 October. The rest of the lakes have their overturn on 12 and 13 October. Typically deep lakes cool slower, and therefore overturn occurs later, but sheltering and mild winds affect that significantly. Lakes Vanajanselkä and Jääsjärvi are easily mixed and their depth is not able to delay their cooling.

The mean depth of the thermocline and its temperature vary according to the situation: in the shallowest small Lake Valkea-Musta the depth is naturally much smaller (4.7 m) and the temperature higher (13.4°C). In the deeper lakes heat can penetrate lower. The values are similar in each lake: Lakes Jääsjärvi: 9.9 m and 11.7°C, Lake Vanajanselkä: 12.3 m and 12.4°C and Lake Kallavesi: 10.3 m and 12.5°C. They can reach roughly the same equilibrium with the atmosphere. In Lakes Näsijärvi and Pääjärvi the thermocline temperature is about 11°C in both of the lakes. In Lake Pääjärvi the depth is 11.3 m, but in Lake Näsijärvi sheltering is not as intense and the thermocline is deeper, to 14.7 m.

Table 4 shows the maximum and minimum values of the average thermocline depth with corresponding temperature, thus describing their range. The years in which those values are obtained are also given, stressing that these factors are not explained merely by morphological differences. It is natural to think that weather strongly affects the smallest thermocline depth found: when it is small the climate has had a relatively small effect. For three of the lakes this occurs in the same year, 1960. Also the greatest depth is obtained in those three lakes in the same year, 1987. These lakes are Lakes Valkea-Musta, Kallavesi and Pääjärvi, which are regularly stratified. The heat exchange is complicatedly affected by several factors in any case. Lake Näsijärvi is also regularly stratified, and in those two years its extremes are also almost reached. In the summer of 1960 the winds are relatively weak, well over one SD below average. The temperature of air in that summer was about the seventh highest over the whole period, which intensifies the heat intake. These factors explain the small epilimnetic depth naturally. In summer 1987 short wave radiation is

Table 4 Largest and smallest depths of the calculated thermocline in the study lakes together with the corresponding years and mean temperatures

Lake	Greatest depth of the thermocline (m)	Year	Temp. (°C)	Smallest depth of the thermocline (m)	Year	Temp. (°C)
Valkea-Musta	5.3	1987	11.6	4.1	1960	13.6
Jääsjärvi	12.3	1967	12.5	6.8	1978	15.6
Vanajanselkä	18.4	1968	10.6	6.5	1983	17.3
Näsijärvi	17.4	1976	11.0	12.0	1997	12.1
Kallavesi	13.7	1987	11.2	7.5	1960	13.1
Pääjärvi	15.1	1987	9.7	7.5	1960	10.7

calculated to have on average its second smallest absolute value over the whole period. In that summer the average air temperature is also the fourth lowest. The least short wave radiation is calculated for summer 1981, but that year air is relatively warm, which seems to be able to feed heat in and no special values are obtained. Large depths can be understood with small heat intake and smaller temperature differences between epi- and hypolimnion: water is more easily mixed to deeper depths. Smaller thermocline depths are obtained with higher temperatures. The largest variation and large values are also seen for Lakes Jääsjärvi and Vanajanselkä, which stratify more irregularly and heat can be more easily be mixed deeper. The shallowness and small area strongly affect Lake Valkea-Musta, which has the greatest depth of the thermocline, 5.3 m, while in Lake Kallavesi it is 13.7 m and in Lake Pääjärvi 15.1 m. The largest and smallest depths are reached the same years in those three lakes in any case, in spite of their differences. In Lakes Näsijärvi, Kallavesi and Pääjärvi, which are rather regular lakes the mean temperature of the thermocline is typically between 10–13°C and the depth is 11–12 m.

This paper is concerned with presenting the main results on stratification during summer. The results from more detailed winter period calculations will be presented in a future paper (Elo 2005). Anyhow it is worth noting that there is an important variation in ice break-up. This can be important, especially for small and sheltered lakes, which stratify easily when surface water is heated. Sometimes some fixed date is assumed for a isothermal starting profile. According to the calculations used in this paper Lake Valkea-Musta's ice was broken at the earliest on 19 April, on average on 5 May, and on 19 May at the latest. Stratification followed almost immediately the date of the earliest ice break-up and also the average, but when the ice breaks up late, stratification was formed about a week after that. This example shows that there is considerable variation in the conditions in different springs, and it is not possible to find one calendar date which could present the isothermal situation every year.

Conclusions

Morphology has important effects on the temperature conditions of lakes. These need to be taken into consideration to obtain realistic lake models with wide applicability. It needs to be considered in the treatment of meteorological data and also in the calculation of mixing in water, which are interconnected. It was still possible to use data from one land station with systematic corrections based on surrounding stations. It was possible to solve seasonal development for six morphologically different lakes in the vicinity. Actual lake data were needed for successful model applications. Still, there were occasions when the solved vertical temperature structure could be improved. The probable cause is that local weather differences can be important in these situations. Optical properties inside the water were not very important and most of the applications were successful with about the same light extinction coefficient. The water in all these lakes is rather dark and the secchi depths are not large. In more transparent water, and particularly in deeper lakes, optical properties are often more important. That is worth considering in new model studies. Further, related numerical problems should be considered.

The formation of stratification is critical for successful modelling and it is easier when stratification is strong. Many important effects are consequently dependent on the existence of stratification, e.g. interactions along the whole depth. Ideally, in lake studies, the summer period should not be separated from the whole yearly cycle, especially for lakes which during winter do not have ice cover (noted also by Peeters *et al.* 2002). There can be important effects resulting from changing climatic conditions, especially if ice cover is formed only for a short time and winter periods with weak stratification increase. During summer typically stratification is predicted to become stronger as the temperature of the air increases (Elo 1998).

The results give information which can be related to morphology. For these lakes with sizes varying from 0.14–257 km^2 and depths varying from 10.5–85 m, the most important features are the relative openness of the lake combined with its volume and heat intake capability: if the ratio of surface area to depth is large enough (for these lakes about 3–5 km^2/m) climate dominates and the lake can be heated freely. When the depth, volume and heat absorbed are large enough the lake stays stratified longer and cools with a corresponding delay. If this ratio is smaller (for these lakes less than 1 km^2/m) the volume of the lake limits heat intake and the heat is blocked into the epilimnion. For very small lakes (ratio less than 0.01 km^2/m and even smaller) shallowness also hinders the deepening of the thermocline. Sheltering becomes increasingly important, including many micrometeorological effects. These can be related to physical factors, and with the dynamics of the lakes their thermal development can naturally be explained.

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