Master of Science Thesis

Development of temperature and respiratory gases during summer stratification in two lakes in southern Finland

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ABSTRACT

Hypolimnetic density currents and oxygen consumption were studied in Lakes Pääjärvi and Ormajärvi in southern Finland during the summer stratification period of the year 2004. Water temperature, dissolved oxygen and dissolved inorganic carbon data were collected from both lakes to detect the possible density currents from changes in temperature and respiratory gases. Additional data of air and sediment temperature, rainfall and chlorophyll *a* concentration was also used in the interpretation of the results. Periodical warming of hypolimnion indicated, that internal seiches have strong influence on heating and distribution of respiratory gases in the upper hypolimnion in both studied lakes. Although no clear signs of hypolimnetic density currents near sediment water surfaces were found during the stratification period, some features of density currents occurring during early stratification were seen especially in Lake Ormajärvi. The results suggest, that during stratification hypolimnion is affected by currents with various origins, element exchange between water and sediment and organic matter fed from the epilimnion. All these contribute to the development of the concentrations of respiratory gases and consequently may influence, for example, the leakage of nutrients from the sediment.

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TIIVISTELMÄ

Tiheyseroista johtuvia pohjavirtauksia ja alusveden hapenkulutusta tutkittiin Pääjärvellä ja Ormajärvellä eteläisessä Suomessa kesäkerrostuneisuusjakson ajan vuonna 2004. Veden lämpötilan, liuenneen hapen ja liuenneen epäorgaanisen hiilen aineistot kerättiin molemmista järvistä, jotta mahdolliset virtaukset voitaisiin jäljittää lämpötilassa ja hengityskaasujen pitoisuuksissa tapahtuvista muutoksista. Lisäksi käytössä olivat tiedot ilman lämpötilasta, sademäärästä ja *a*-klorofyllistä, sekä sedimentin lämpötilasta keväällä 2005. Alusveden jaksoittainen lämpeneminen ilmensi, että väliveden heilahteluja aiheuttavilla sisäisillä aalloilla on suuri vaikutus erityisesti alusveden yläosien lämpenemiseen, sekä hengityskaasujen pitoisuuksiin eri vesikerroksissa. Vaikkei selviä tiheyseroista johtuvia pohjavirtauksia ollut havaittavissa näytteenottojakson aikana, merkkejä tiheysvirtauksista kerrostuneisuuskauden alussa oli nähtävissä erityisesti Ormajärvessä. Tulokset osoittavat, että kerrostuneisuuden aikana alusveteen vaikuttavat montaa eri alkuperää olevat virtaukset, veden ja sedimentin välinen aineiden vaihto sekä päällysvedestä laskeutuva orgaaninen aine. Kaikki nämä tekijät vaikuttavat hengityskaasujen pitoisuuksiin alusvedessä ja esimerkiksi mahdolliseen ravinteiden poistumiseen sedimentistä.

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1. INTRODUCTION

Oxygen is diffused into water from the atmosphere and produced photosynthetically in the photic zones of surface waters. All aerobic aquatic organisms use oxygen in their metabolism, so the distribution and dynamics of oxygen in water, and especially the consumption of dissolved oxygen are the basics to understanding the functioning of lakes and rivers. Consequently oxygen is one of the most essential parameters of inland waters (Wetzel 2001).

In lake ecosystems the most intense biological activity occurs in the sediment-water interface (Krumbein *et al.* 1994), and the lifespan and productivity of a water body are highly dependent of the reactions and processes occurring at that site (Wetzel 2001). Sediments have large surface area, contain plenty of organic matter, and they are physically relatively stable, which enables the sufficiently high biological and chemical activity. In addition to organic matter sediments are typically rich in essential nutrients, even 1000-fold richer than water column, and therefore heterotrophic bacteria have a good habitat for growth (Pace and Prairie 2005). It is estimated that approximately 50 %, sometimes even up to 80 % of hypolimnetic metabolism is benthic (Lund *et al.* 1963, Cornett and Rigler 1987). According to Granéli (1978), oxygen availability and temperature seem to regulate seasonal variations in sediment oxygen uptake. Accordingly he found the Q10 values determined for the cold waters (5-10 ºC) in the interval from 2.0 to 3.0. Therefore even small changes in hypolimnetic temperatures may be crucial increasing oxygen comsumption during stratification period and affecting late summer and late winter oxygen concentrations near sediments and thus in the whole hypolimnion.

Although current measurements near sediments have been studied especially in large lakes exposed to wind (e.g. Serruya 1975), fairly little is known about hypolimnetic currents. Bottom currents have been measured only few times in smaller lakes and in most studies typical values for these currents are found to be rather small, around 0.01 m s^{-1} (e.g. Lemmin and Imboden 1987, Wüest *et al.* 1988). Distribution and fluxes of oxygen and nutrients affect the ecology of the entire lake, consequently sediment surfaces affected by currents and mixing are important sites affecting the dynamics of those substances. Lake sediments are both source and sink for biological and chemical substances depending on the prevailing conditions, and therefore bottom currents in hypolimnion may strengthen the eutrophication, when more nutrients are carried to the photic productive zones (Imboden *et al.* 1983). Simultaneously gas fluxes and their mixing processes are affected, i.e. increasing oxygen consumption, because of increasing contact between water and sediment. Hypolimnetic oxygen consumption is generally accepted to be mainly dependent on the relative volume of the hypolimnetic water mass of the total one. Because many low productivity lakes with high relative volume of hypolimnion have higher than expected oxygen depletion rates during summer stratification period, not only biological processes but also hydrodynamic ones are expected to be responsible for the increased oxygen depletion rates.

Low concentrations of dissolved oxygen in the hypolimnion of lakes are often symptoms related to eutrophication processes (Maciej and Kowalczewski 1981, Horne and Goldman 1994). Therefore hypolimnetic currents may have bigger effect on the eutrophication than previously thought. It has been noted, that long-lasting water currents at the sediment-water interface of 5-6 cm s^{-1} can result in a rather high (> 2 times higher) increase in sediment oxygen demand compared to the rates during the calm periods (Beutel 2001). Fastened oxygen depletion in hypolimnetic zones of lakes is an ever increasing problem, and may lead to severe ecological consequences, i.e. zooplankton and fish adapted to cold oxygenated waters are facing habitat loss (Cooper and Koch 1984, Doke *et al.* 1995, Field and Prepas 1997). When eutrophication casts its shadow especially over smaller and shallower human-impacted lakes, many of which have high amenity value, understanding the hypolimnetic currents near sediment-water interface are important to be identified in order to understand the processes truly, and to be able to draw the right conclusions when planning for example restoration actions.

The main hypothesis of this Master's thesis was, that if the sediment is after winter significantly colder than the overlying water at the early period of stratification, the water would release heat to the sediment. Colder and denser water would then slowly flow to deeper areas on the top of the sediment and absorb dissolved substances from the sediment along the way. This creates a slow current and water replacement, when flowing water sets to the depth where the density of the replaceable water is the same. Part of the flowing water still in contact with the sediment continues to release heat and gain dissolved substances, and flows even deeper down the slope. Hypolimnetic water would now face upwelling and mixing, and flux of nutrients and gases i.e. oxygen and carbon dioxide may be strongly influenced.

2. BACKGROUND OF THE STUDY

2.1 Stratification of temperature

Seasonal stratification and the depth to which mixing is limited by stratification are probably the most important physical factors determining the characteristics of lakes in temperate regions. In spring ice covers of lakes deteriorate and surface waters are then exposed to direct sunlight and wind stress. Water in all depths is now nearly isothermal and thus readily exposed to mixing. Spring turnover is essential in the formation of summer oxygen concentrations and temperatures in hypolimnion. As spring is slowly turning into summer, surface waters of lakes are starting to heat more rapidly than the mixing can distribute the heat. When surface and deep water layers are becoming more divergent and more resistant to mixing, the water column begins to stratify. Vertical mixing decreases with progressing stratification, meanwhile the horizontal eddy diffusion increases with proceeding stratification (Nyffeler *et al.* 1983). A well mixed, significantly warmer layer than in the deeper areas of the lake is developing into the surface of the lake, which is epilimnion. The colder lowest layer of the watermass is called hypolimnion. In the early summer temperature in hypolimnion is mostly determined by the final temperature when water is still mixing at spring turnover. Thermocline or metalimnion is the layer in which the vertical change (gradient) in temperature is highest. In practise, thermocline can be determined to the depth where temperature gradient is greater than 1 ˚C per meter (Huttula 1976). Depth of thermocline is primarily dependent on the surface area of the lake (Gorham and Boyce 1989).

2.2 Sediment temperature

Lake sediments are both sources and sinks of heat depending on the time of the year. During winter sediments release heat to water, whereas during summer water releases huge amounts of heat energy to sediment (Birge *et al.* 1928). Sediment temperatures follow closely seasonal oscillations of water temperatures in shallow depths, but in greater depths there can be significant time lags in the responses of sediment temperature to the temperature of water mass. This is likely due to more intense absorption of solar energy by sediment at shallow depths (Dale and Gillespie 1977). Therefore also sediment heat budgets of shallow and bigger depths differ significantly so that the flux of heat in shallow depths can be highly significant when thinking for example the heat budget of the whole lake.

Difference in sediment composition can cause spatial differences in its temperature. Variations in sediment temperatures tend to occur normally in first few meters in sediment, and in deeper sediment depths of over four meters the annual differences are usually minimal (Likens and Johnson 1969).

2.3 Stratification of oxygen concentration and oxygen consumption in hypolimnion

During spring turnover and in early summer in oligotrophic lakes stratification of oxygen concentration can be orthograde (Åberg and Rodhe 1942), in which oxygen concentration is lowest in the epilimnion and highest in the hypolimnion. This is mostly due to physical factors during stratification, which cause warming of epilimnion and therefore the decrease of oxygen concentration. On the other hand, temperatures are decreasing in metalimnion, which ensures the increased oxygen concentrations (Wetzel 2001). Much more common is clinograde oxygen profile (Åberg and Rodhe 1942), which occurs in productive lakes where large amounts of organic matter reach hypolimnion and speeds up oxygen consumption. Fast depletion of dissolved oxygen concentration enables profile, in which dissolved oxygen concentration is highest in the epilimnion and lowest in the hypolimnion. During clinograde oxygen profile metalimnetic oxygen maximum or minimum may occur, which are quite common in lakes. Metalimnetic oxygen maximum is normally due to high primary production in metalimnion. Metalimnetic oxygen minimum occurs, when organic matter is falling towards the bottom of the lake, relatively higher portion of decomposition occurs in the upper part of the lake in which temperature is higher, than in colder hypolimnion in which the more slowly decomposing matter remains.

Beside the most important factors affecting hypolimnetic oxygen consumption mentioned above, processes occurring near sediment surfaces need more attention. The mineralization of organic material in lake sediment influences the conditions of the overlying water, but sediment metabolism is mostly controlled by chemical, physical and biological processes occurring in sediment (Granéli 1978). Granéli also found, that freshly sedimented organic material seem to be of minor importance in determining the seasonal changes in sediment oxygen uptake. Hypolimnetic dissolved oxygen is mostly consumed by micro-organisms that degrade organic matter sinking from productive surface waters. Therefore increasing rates of hypolimnetic oxygen consumption are often due to eutrophication processes (Maciej and Kowalczewski 1981). Maciej and Kowalczewski also found, that especially in large lakes eutrophication is observed first in oxygen depletion rates in hypolimnion rather than in shallower Secchi disk depths or increased chlorophyll *a* concentrations. Beutel (2001) has found experimentally, that to avoid ammonia accumulation in lake deeps, relatively high concentrations of dissolved oxygen (ca. 10 mg l^{-1}) should be available at the sediment-water interface to ensure adequate oxygen flux into the sediment. In eutrophicated lakes this is seldom true, because of high amount of organic material and related high respiration rates. The end-of-summer oxygen profile is mainly dependent on the duration of spring turnover, meteorological conditions prevailing during summer, on the form of the lake basin, and on the rate of hypolimnetic oxygen consumption.

2.4 Factors affecting oxygen consumption

Amount of organic matter is the most important factor enabling and regulating respiration, and effect of organic matter on oxygen consumption rates have been reported e.g. by Ahrens and Peters (1991). Tomaszek and Czerwieniec (2003) found no connection between oxygen consumption rates and the concentration of organic matter in sediment, but this might have been due to other environmental factors. Hopkinson *et al.* (2001) found, that there was a strong relationship between sedimentation of phytoplankton and oxygen consumption. Apart from organic matter, water temperature is undoubtedly the most important factor affecting oxygen consumption and respiratory rates in lake ecosystems. Rising temperatures increase oxygen consumption rates significantly in sediments (Upton *et al.* 1993, Hopkinson *et al.* 2001 and Tomaszek and Czerwieniec 2003) as well as in the whole water column. In general higher temperatures increase the metabolic rates and activity of organisms simultaneously increasing oxygen consumption rates. Other factors known to affect respiration and oxygen consumption rates are oxygen concentration, pressure, light, turbulence, pH, salinity and lake trophic level (Hernández-Leon and Ikeda 2005).

Oxygen concentration seems to regulate oxygen consumption only when concentrations are fairly low. For example Cornett and Rigler (1984) found that oxygen consumption decreases only when oxygen concentration falls below 1 mg l^{-1}. In a range from 1-12 mg l^{-1} no signs of changing oxygen consumption rates were found. When oxygen concentration is very low in water near the sediment surface, it seems to regulate oxygen consumption most intensely, but at higher oxygen level temperature is the major controlling factor in the sea (Cowan *et al.* 1996). Provini (1975) has found similar results from lakes. Pressure does not normally affect respiration rates in lakes, although in seas and very deep lakes this may not be true. Light affects oxygen consumption significantly so that consumption rate can be higher in the light than in the dark (eg. Chalker *et al.* 1983). Turbulence probably increases oxygen consumption little up to certain point (Bailey *et al.* 1994, Hernández-Leon and Ikeda 2005). Effects on pH have not been widely reported, although in small lakes some effects may be found (Hernández-Leon and Ikeda 2005). Salinity changes cause osmotic instability in organisms, and may cause increased and decreased respiration rates depending on group of organisms (Hernández-Leon and Ikeda 2005). However, in lake ecosystems effects of salinity may be minor apart from salt lakes in hot and dry areas. Of course biomass of organisms have a great effect on oxygen consumption rates, which Nakamura (2003) proved with macrobenthos. Especially changes in biomass of bacteria and benthic organisms play a major role in determining hypolimnetic oxygen consumption rates. Beutel's (2001) results have a great importance, because they indicate that long-lasting water currents near sediment surfaces can increase sediment oxygen consumption significantly.

2.5 Respiration quotients

Modelling respiration processes that occur in the whole ecosystem are rather difficult and no widely satisfactory method has been introduced. Calculating respiration quotients (RQ) is one and probably the best solution, in which the oxygen deficit can be compared to the evolution of carbon dioxide but it has also some disadvantages. Respiration quotients were originally tools developed to model respiration at organism level, but especially in aquatic environments they are effective in describing respiration in community and ecosystem level.

Oxygen uptake of sediments in lakes is generally supposed to be slightly higher than the evolution of carbon dioxide. This is mainly because respiratory quotients (RQ = CO_2/O_2) of oxidation processes of fats and proteins are normally less than one (Rich 1975). According to Ohle (1952), respiration quotients that are estimated for inland waters get generally values of about 0.85. In sediments with anaerobic metabolism carbon dioxide is no longer the only end product of degradation of organic matter and it is evolved without the consumption of O_2. Therefore anaerobic metabolism of prokaryotes can increase respiration quotients significantly higher than one (Murray and Rich 1995). Then in sediment-water interface less O_2 is entering to the sediment than CO_2 is released to the water.

Empirical respiration quotient values are normally calculated by measuring the rates of dissolved CO_2 evolving and dissolved oxygen disappearing from water (Hutchinson 1957). Rich (1975) found with simple calculations, that > 60 % of hypolimnetic respiration was anaerobic, and > 40 % of hypolimnetic carbon was, in theory, available for chemosynthetic processes. During stratification period the hypolimnetic respiration quotient values tend to vary with the availability of oxygen, and therefore respiration quotients in hypolimnion generally increase with the duration of stratification and with increasing depth.

2.6 Hypolimnetic currents

Mixing processes at the sediment-water interface are still not very well understood. Because of the slow current speeds of the order of 0.01 m s^{-1} (Lemmin and Imboden 1987, Wüest *et al.* 1988), the measurement of hypolimnetic bottom currents is demanding. Measuring bottom currents directly in short time periods would require highly sensitive current meter, recording current speeds well below 0.01 m s^{-1}. Still, the ecological significance of these slow currents may be relevant for the whole lake ecosystem as noted in the introduction. In stratified lake, hypolimnetic water exchange can have its initial force either from above or below. The latter can be triggered by groundwater intrusion from the lake bottom, the former by currents caused by density differences of water masses (Simpson 1982). The penetration of heavier water into hypolimnion can cause upwelling of hypolimnetic water and mixing in lake deeps. During stratification period, the kinetic energy is affecting the movement of water mostly horizontally. In metalimnion Kelvin-Helmholtz instability (Horne and Goldman 1994) may cause internal waves and seiches to occur, which can induce horizontal and vertical movement into the hypolimnion. Also river waters flowing into lakes can cause bottom currents because of differences in temperature and chemical composition between lake and river water (e.g. Lambert *et al.* 1976).

In relatively small lakes internal seiches are probably the most important factors affecting water movements in hypolimnion (Hutchinson 1957). Internal seiches occur, when wind blows strongly for a relatively long time from the same direction causing accumulation of epilimnetic water to one end of the lake, and respective upwelling of hypolimnetic water at the other end. The rising of water surface level on one end of the lake causes water mass to be pulled downwards until it faces the denser water layer in the thermocline. This density difference causes water to flow back near metalimnion to the opposite direction of the wind. The result from this is rhythmical continuous movement of water masses into opposite directions without much change in lake surface level. Internal seiches can also induce currents that intrude down to the hypolimnion as well, causing horizontal and vertical transport of dissolved substances and especially heat from upper water layers to the lower ones. Mortimer (1952) has provided a clear presentation of the structure and dynamics of daily existence of internal seiches in a stratified Lake Windermere.

Bottom current have been directly measured only few times but there is no doubt that these currents really exist during summer stratification. These rather slow currents become significant when occurring constantly over long periods of time. Long-lasting heavy storm periods can induce temporary currents that can be even ten times higher than in normal calm periods (Wüest *et al.* 1988). During such events, periods of intensive water exchange and mixing of deep hypolimnetic water may exist, because generated currents can produce shear and turbulence that to a great extent contributes to the vertical mixing.

The existence of density currents in hypolimnion is well established in very different kind of lakes, by Alsterberg (1930 and 1931) in small Swedish lakes and by Langmuir (1938) in Lake George. Hutchinson (1957) has nicely explained these processes occurring in the hypolimnion: during the summer when stratification has set in, the hypolimnetic water in close contact with the sediment at intermediate depths will tend to lose heat to the sediments. It should be noted that still the density of contact water is about to increase, because the initial temperature of water was above the temperature of maximum density 4 ˚C. There might also be movement of dissolved materials in the sediment-water interface, and these substances will further contribute to the increase in the density of water (Joller 1985). The effect of dissolved gases on water density is usually negligible. The denser water will then flow down the slope of the basin. If the increase in water density is solely caused by the loss of heat to the sediment, water should flow into a layer at which the replaceable water is isothermal with the flowing water coming from above. Then the colliding water masses would either mix or replace each other. The significance of this process would be the cold-water intrusion into deeper water layers. But if there is also dissolved substances affecting the density of the flowing water mass, then the water would flow into the level in which the existing water is slightly colder than the replaceable water, consequently bringing heat to the deepest parts of the lake. In these kind of processes large water masses are involved. Therefore ecological significance of these processes can be higher than expected.

2.7 Research group

This research was made as a part of professor Kalevi Salonen's and his research group's project dealing with the importance of the sediment oxygen consumption in lake deeps especially in wintertime. Now this project was enlarged to consist of summertime observations in order to see if summer conditions give new ideas of density currents to be researched more precisely. The sediment oxygen consumption and processes affecting it have also aroused public interests after massive fish kills due to dissolved oxygen debts during winter and spring 2003 in Finnish lakes and rivers. Also fighting against eutrophication and understanding the processes relating to it are one of the major trends in today's environmental studies.

3. MATERIAL AND METHODS

3.1. Study sites

Data of this study was collected during the summer 2004 from May 18th to September 14th from two lakes in Southern Finland. The study sites, Lake Pääjärvi in Lammi-Hämeenkoski region and Lake Ormajärvi in Lammi region, differed from each other quite dramatically. Lake Pääjärvi is a large, deep and humic lake. Lake Ormajärvi is smaller, shallower and clear-water lake (Table 1). Lake Pääjärvi is still quite unpolluted whereas Lake Ormajärvi has been eutrophicated by effluents from the dairy, piggery and domestic sewage, which up to 1972 were discharged untreated into the lake. However, also Lake Pääjärvi has shown signs of eutrophication during few recent decades (Hakala and Arvola 1994). Over 50 % of the catchment area of Lake Pääjärvi consists of coniferous forests whereas nearly 20 % is cultivated land (Ruuhijärvi 1974). The rest of the catchment area consists of deciduous forests, peatlands and lakes. The catchment area of Lake Ormajärvi is mostly cultivated land and coniferous forest. These two lakes were chosen to the study, because of their favourable location, different trophic status and long-term background information. Because the rate of processes differ between mesotrophic and eutrophic lakes, the selection of these two lakes was thought to give a wider perspective in the studied subject.

Table 1. Characteristics of Lake Pääjärvi (Ruuhijärvi 1974) and Lake Ormajärvi (Ilmavirta *et al.* 1974).

	Lake Pääjärvi	Lake Ormajärvi
Latitude	61° 04' N	61° 06' N
Longitude	25° 08' E	24° 58' E
Altitude (m)	103	94
Catchment area (km^2)	244	
Water surface area (km^2)	13.4	6.6
Volume (m^3)	206 x 10^6	67 x 10^6
Max depth (m)	87	30
Mean depth (m)	14.4	10.3
Water residence time (yr)	3.3	
pH	6.8	7.5
Water colour (mg Pt l^{-1})	50	15
Tot N (mg l^{-1})	0.9	0.65
Tot P (mg l^{-1})	0.014	0.27
Conductivity (μS)	76	143

3.2. Sampling and data collection

Sampling in both lakes was always made in the deepest point of the lake. The points were marked with buoys. Dissolved oxygen (O_2), dissolved inorganic carbon (DIC) and temperature were measured from both lakes, to detect the hypolimnetic currents from changes in temperature and concentrations of respiration gases. Similar kind of approach with measurements of temperature and chemical parameters, has been used by Mortimer (1941, 1942). Samples were taken from surface to near the bottom so that the first sample was taken one meter below the surface, the next from five meters below the surface and from that point on in every five meters. Therefore the deepest point in Lake Pääjärvi was at 75 m and at 25 m in Lake Ormajärvi. There were 13 sampling occasions in Lake Pääjärvi between May 18th and September 14th and 12 sampling occasions in Lake Ormajärvi between May 24th and September 13th. Samples were taken weekly till the early part of July and thereafter less regularly until September 14th. Samples were taken at the same time of the day between 9.00 am and 12.00 am in every occasion.

The surface area and volume under 60 m in Lake Pääjärvi (Fig. 1) and under 25 m in Lake Ormajärvi (Fig. 2) are so small compared to upper parts of lake, that the significance of these deep water zones become less important when considering the magnitude of hypolimnetic density currents and their ecological significance. Therefore my work concentrates mainly on zones between 30-60 m in Lake Pääjärvi and between 10-25 m in Lake Ormajärvi.

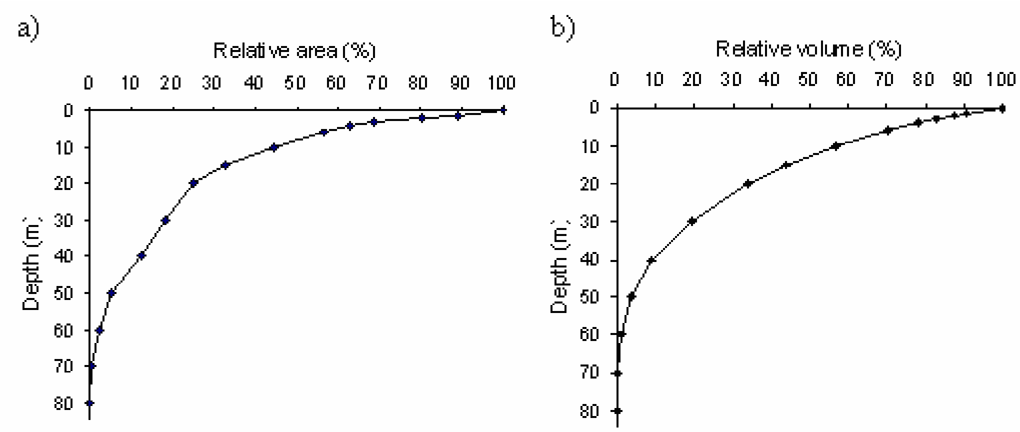

Figure 1. Hypsographic curves of relative area (a) and relative volume (b) of Lake Pääjärvi.

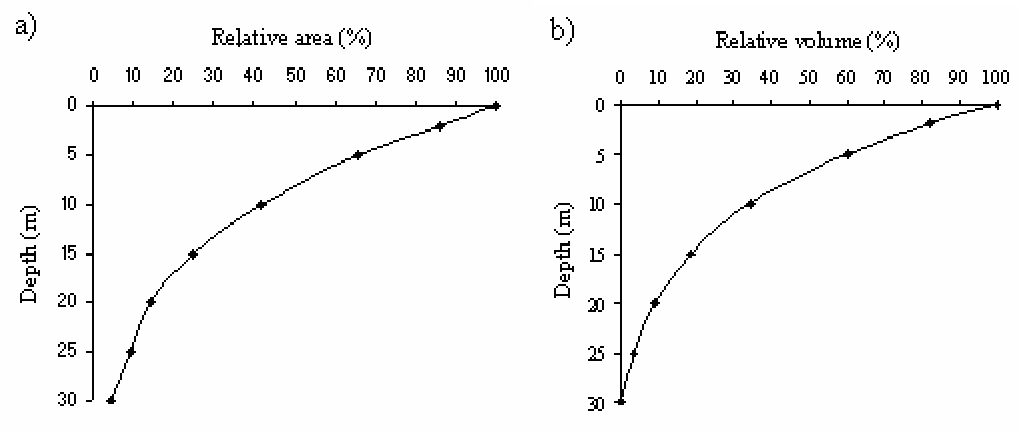

Figure 2. Hypsographic curve of relative area (a) and relative volume (b) of Lake Ormajärvi.

3.2.1 Temperature

Temperature data was collected with automatic loggers that collected temperature data in two-hour intervals in Lake Pääjärvi. Loggers in Lake Pääjärvi were located at the deepest point of the lake and they recorded data in every five meters from one meter below the surface down to 75 m. For the stratification period temperature data that matched the dissolved oxygen and dissolved inorganic carbon sampling dates was used. However, when there were longer time intervals than one week in collecting dissolved oxygen and dissolved inorganic carbon data, weekly temperature data was used. Logger temperature at time 10.00 am was used in every occasion, because it normally matched the dissolved oxygen and dissolved inorganic carbon sampling time most precisely. Also precise time series from temperatures measured in every two hours was used for hypolimnion to detect the short-time oscillations. In 2004 sediment temperatures couldn't be collected and therefore temperatures of sediment and overlying water from Lake Pääjärvi at 20 and 40 m in early May of the year 2005 were used to give some perspective about the differences in temperature between sediment and water. Loggers collected data in every half an hour, and daily means were used.

In Lake Ormajärvi loggers did not work properly, so the data collected by Anne Ojala's research group (University of Helsinki) was used, which was collected by using YSI-meter (Yellow Springs Instruments) at the same time and from the same depths as the oxygen and dissolved inorganic carbon samples. In Lake Ormajärvi temperature data was collected from one meter below the surface down to 25 m in five meter intervals.

3.2.2 Dissolved oxygen

O_2 and dissolved inorganic carbon samples were collected with Limnos sampler (volume 2 l). O_2 samples were poured to 100 ml glass bottles, whereas 50 ml glass bottles were used for dissolved inorganic carbon samples. Bottles were put into a box with crushed ice until determination. Determination of oxygen samples was made with transformed Winkler′s titrimetric method according to SFS standard 3040 (1990). Titrations were made with piston burette manufactured by Metrohm AG Herisau, Switzerland, with a precision of 0.01 ml. All the determinations were made during the same day when the samples were taken. Precipitation reagents were added in the lab just before beginning the titration in order to avoid the lost of oxygen equivalents after reagent and acid (H_2SO_4) addition (Carignan *et al.* 1998). The concentration of dissolved oxygen was calculated with the following equation:

$$C_x = \frac{8000 \cdot V_3 \cdot c \cdot V_0}{(V_0 - V_t)\, V_n}$$

in which
C_x is the concentration of dissolved oxygen, mg l^{-1}
V_3 is the volume of sodium thiosulphate ($Na_2S_2O_3 \cdot 5H_20$) solution used in titration of a sample, ml
c is the concentration of sodium thiosulphate solution (0.01 mol l^{-1} in this study)
V_0 is the volume of sample bottle, ml
V_n is the titrated volume of the sample, ml ($V_0 – 25$ ml)
V_t is the summed volume of precipitation reagents (3 ml); 1 ml of manganous chloride solution ($MnCl_2 \cdot 5H_20$) and 2 ml of alkaline iodide solution
8000 is the coefficient $\frac{1000 \cdot 32}{4}$ (4 moles of sodium thiosulphate equals 1 mole of oxygen).

Calculations of oxygen saturation were made with the calculator on the website of the University of Jyväskylä (http://www.paijanne.org/kyllastysaste.php). Calculations of oxygen consumption rates in both lakes were made either using linear regression method (time vs. oxygen concentration) or the absolute difference between concentrations at the beginning and the end of certain periods.

3.2.3 Dissolved inorganic carbon

Determinations of dissolved inorganic carbon were made with a method based on acidifying and bubbling, in which the released CO_2 was measured with infra-red gas analyzer (Salonen 1981). Five replicate injections into the bubbling chamber were made from each sample bottle with a 0.2 ml syringe. Median values were used instead of means, because in this way the effect of possible failures in injections could be objectively excluded. Every time when the determinations were made, the device was calibrated with ion-changed water (blank) and two $NaHCO_2$ solutions of different concentrations. Calibration coefficients were plotted against time and analyzed using linear regression to see if there was any trend in K (Figs. 3 and 4), although none of the statistical prerequisites were fulfilled. Because the carbon analyzer is typically very stable, the same median calibration coefficient might be used, if no significant trend with time could be observed. There was a significant trend in calibration coefficients in Lake Pääjärvi (linear regression:

n = 13, $P < 0.01$, $R^2 = 0,5$) and no significant trend in Lake Ormajärvi (linear regression: n = 12, $P = 0.16$, $R^2 = 0.19$). It was reasoned that most precise results in both lakes can be obtained if the dissolved inorganic carbon results were calibrated by the median value from all of the calibration coefficients except those done in May. There must have been some system change (e.g. replacement of gas tubings) affecting calibration. This assumption gets support from oxygen results which did not show any comparable change from May to June. Consequently May determinations were calibrated separately using their median calibration coefficient. Using this procedure the concentrations measured in May might have been slightly too high - even higher than the concentrations of later sampling dates (Figs. 31 and 32) which is theoretically unlikely, this solution was thought to give the most reliable results.

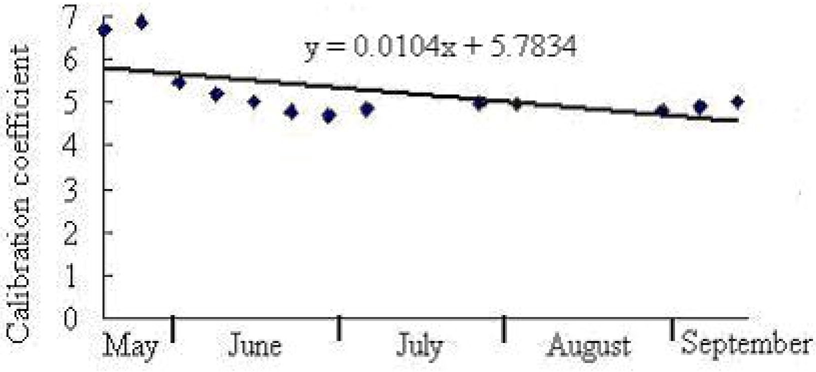

Figure 3. The development of calibration coefficients for dissolved inorganic carbon samples from Lake Pääjärvi. The line represents linear regression.

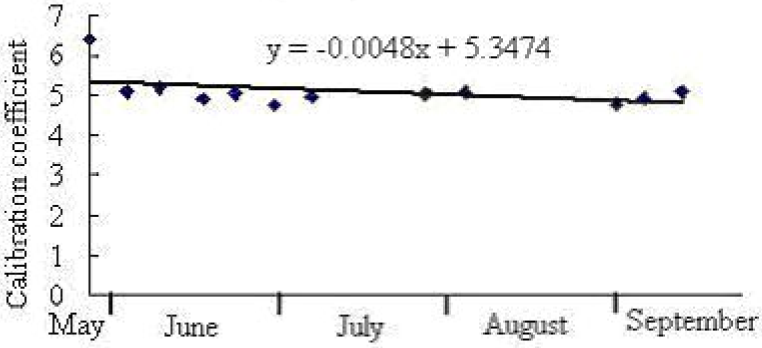

Figure 4. The development of calibration coefficients for dissolved inorganic carbon samples from Lake Ormajärvi. The line represents linear regression.

3.2.4 Chlorophyll *a*

Chlorophyll *a* data from both lakes was collected by Anne Ojala's research group (University of Helsinki) for BORWET-project. The samples were taken weekly as averages from surface water throughout the whole stratification period. In Lake Pääjärvi chlorophyll averages were from depth zone 0-4 m, whereas in Lake Ormajärvi from 0 to 6 m.

3.2.4 Outliers

There were few outliers found in the data, which can probably be explained by the malfunction of water sampler. In those cases dissolved oxygen and inorganic carbon results differed dramatically from the otherwise smooth development of their concentrations. The only explanation can be that the sampler had released already before it reached the intended sampling depth. In Lake Pääjärvi samples taken from 35 m at the 18th of May, from 30 m at the 1st and 8th of June and from 25 and 30 m at the 6th of July, and in Lake Ormajärvi from 25 m at the 3rd of June and 28th of July and from 20 m at the 30th of June were therefore ignored. On the 8th of June sample from 75 m in Lake Pääjärvi could not be taken due to difficult weather conditions, and the sample bottle of dissolved oxygen at 31st of August from 20 m leaked and had to be rejected.

3.2.5 Calculating respiration quotients

Respiration quotients (RQ, $\frac{\Delta \mathrm{DIC}}{\Delta \mathrm{O2}}$ in moles) for both lakes were calculated for each depth in the hypolimnion and the mean value for the whole hypolimnion was used. The oxygen depleted and dissolved inorganic carbon accumulated during those periods were calculated as the differences between distant ends from absolute concentrations. Linear regression was used to estimate respiration quotient values for certain periods so that the regression line was drawn for each depth separately. The difference in dissolved oxygen and dissolved inorganic carbon concentrations for the period were calculated normally from the equation of the regression line, after which the mean respiration quotient value for the whole hypolimnion was calculated.

3.2.6 Weather data

Air temperatures at 04.00 am and 12.00 am were recorded daily at Lammi Biological Station. Also daily rainfall was measured.

3.3 Computer programs

Microsoft Excel 2000 was used in drawing scatter plots, for data storage and for required calculations. Statistical analyses were made using SPSS version 13.0 statistics program. Surfer 8.2-program was used in making contour maps. In every contour map minimum curvature method was used.

4. RESULTS

4.1 Weather

At the end of May noon air temperatures were near to 10 ˚C (Fig. 5). Daily temperatures increased quite steadily till mid August with oscillations of 1-2 week cold and warm periods, after which temperature started to decrease. In late May and early June major fluctuations in temperature (> 10 ˚C) occurred between adjacent days. In early August there was a warm period, during which temperature remained near 25 ˚C for almost a week. Mean temperature for the period from June to the end of August in 2004 was 14.4 ˚C, which fits well within the range of temperature (median 1.6-31.8; range 14.1-16.0 ˚C) for the years 1971-2000 (http://www.fmi.fi/saa/tilastot_143.html). Night time temperatures followed the same pattern as at noon, but due to increasing length of night the daily oscillations increased towards the end of sampling period (Fig. 5). Especially in late August and early September night time temperatures dropped rapidly.

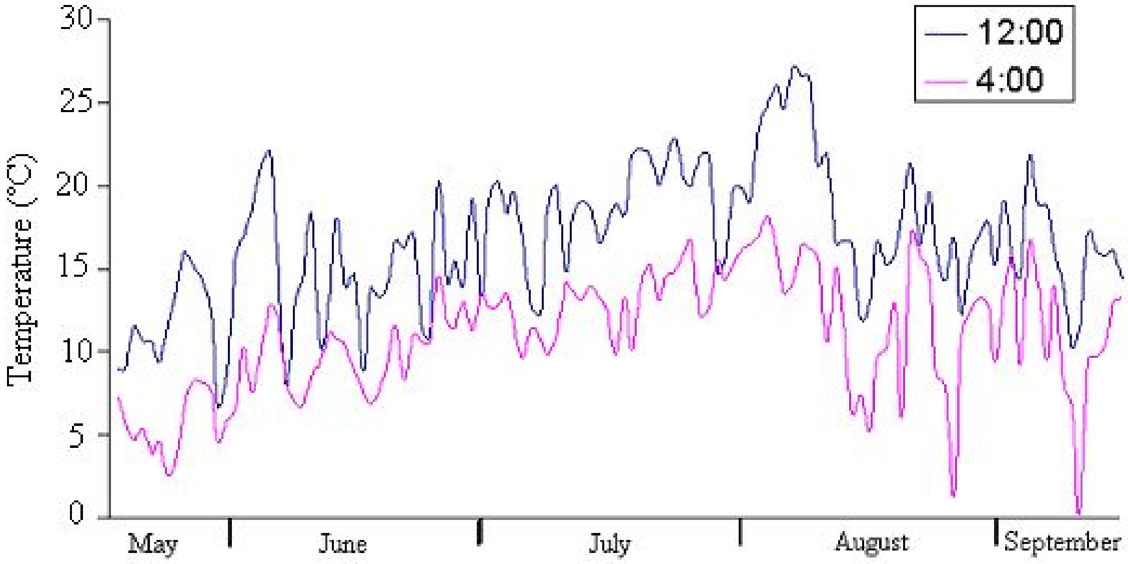

Figure 5. Air temperatures at 4.00 and 12.00 am at Lammi Biological Station during the summer of the year 2004. Data from Lammi Biological Station.

The summer 2004 was very rainy, > 400 mm between June and the end of August, compared to the mean rainfall of ca. 200 mm during the years 1971-2000 at the same period (http://www.fmi.fi/saa/tilastot_143.html). Most of the rain fell down during the two periods from the intercept of June to July and from the intercept of July to August (Fig. 6). At the turn of June to July and late July daily rainfall was over 45 mm per day at single occasions. In early June and from early to mid August the only dryer periods occurred.

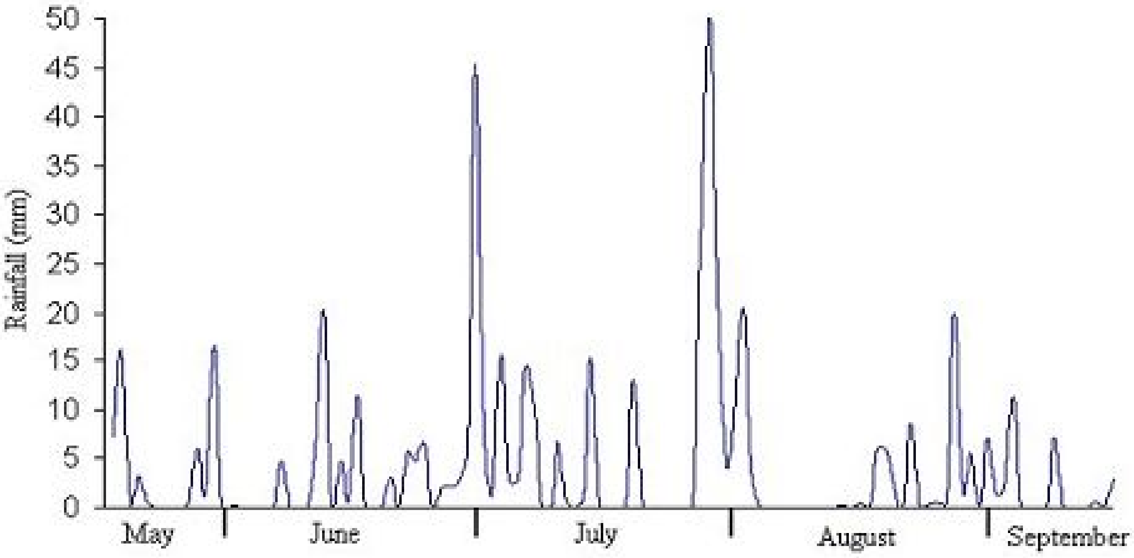

Figure 6. Daily rainfall at Lammi Biological Station during the summer of the year 2004. Data from Lammi Biological Station.

4.2 Lake water temperature

4.2.1 Epi- and metalimnion

In the middle of May, temperature of Lake Pääjärvi was already stratified, and the epilimnion reached down to five meters (Fig. 7). Epilimnion reached nearly 10 m in late June and stayed there with only little deepening until the end of the study period in the middle of September. At the early period of stratification epilimnetic temperature was about 8 ˚C. The highest temperature of 21 ˚C in the epilimnion was reached in early August, and then slowly started cooling (Figs. 7 and 8). Warming of epilimnion was fastest around early June (Fig. 7).

In late May, temperature of Lake Ormajärvi followed the same pattern as in Lake Pääjärvi from surface to 25 m (Figs. 7 and 9). In early June epilimnion reached down to three meters, but had deepened during the summer to over five meters in early July, and even down to 9 m at September (Fig. 9). At the early period of stratification surface temperature was about 11 ˚C, and reached its highest temperature of nearly 21 ˚C at the interface of July to August. Warming intensity remained quite the same from late May to late July, after which epilimnion started cooling (Figs. 9 and 10).

In late May the thermocline in Lake Pääjärvi was at the depth from 5-20 m (Fig. 7). At the early summer the thermocline settled to 5-15 m. The thermocline moved deeper during the course of the stratification period, being from 9 to nearly 30 m at the end of the summer (Fig. 7). In late May, when the stratification of Lake Ormajärvi was fairly weak, the thermocline reached from < 5 m down to 20 m, after which it shallowed to 5-12 m in early June (Fig. 9). Later during the stratification period the thermocline moved deeper, being from 8-15 m at August and even down to 17 m in early September.

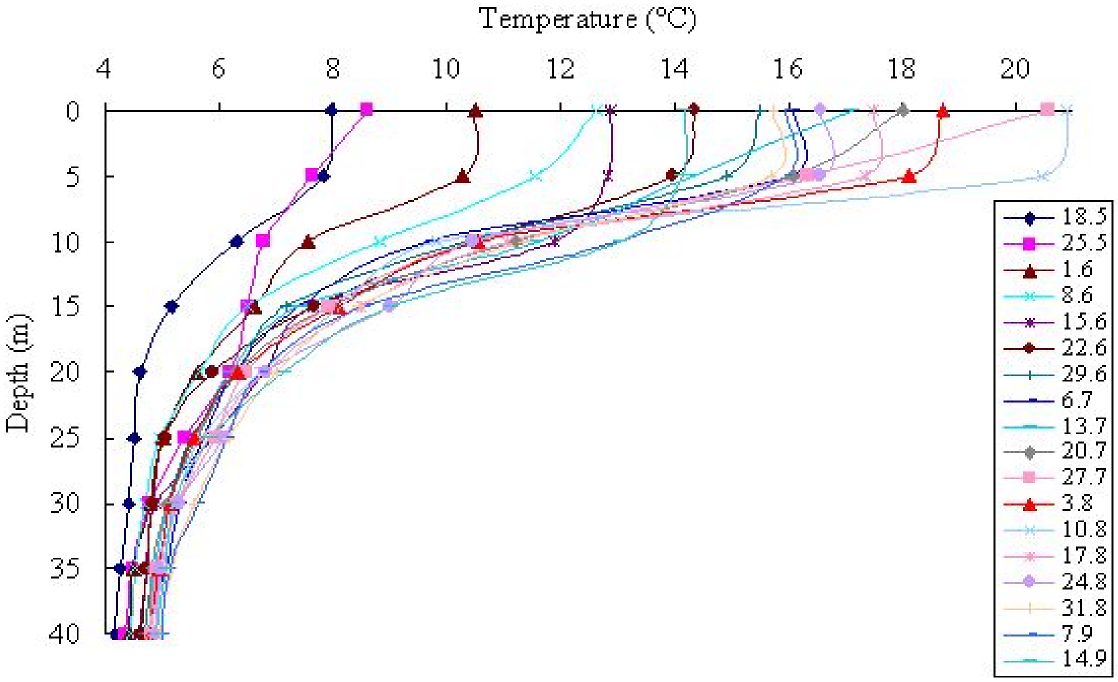

Figure 7. Vertical distributions of temperature at weekly intervals in epi- and metalimnion in Lake Pääjärvi during the summer stratification of the year 2004.

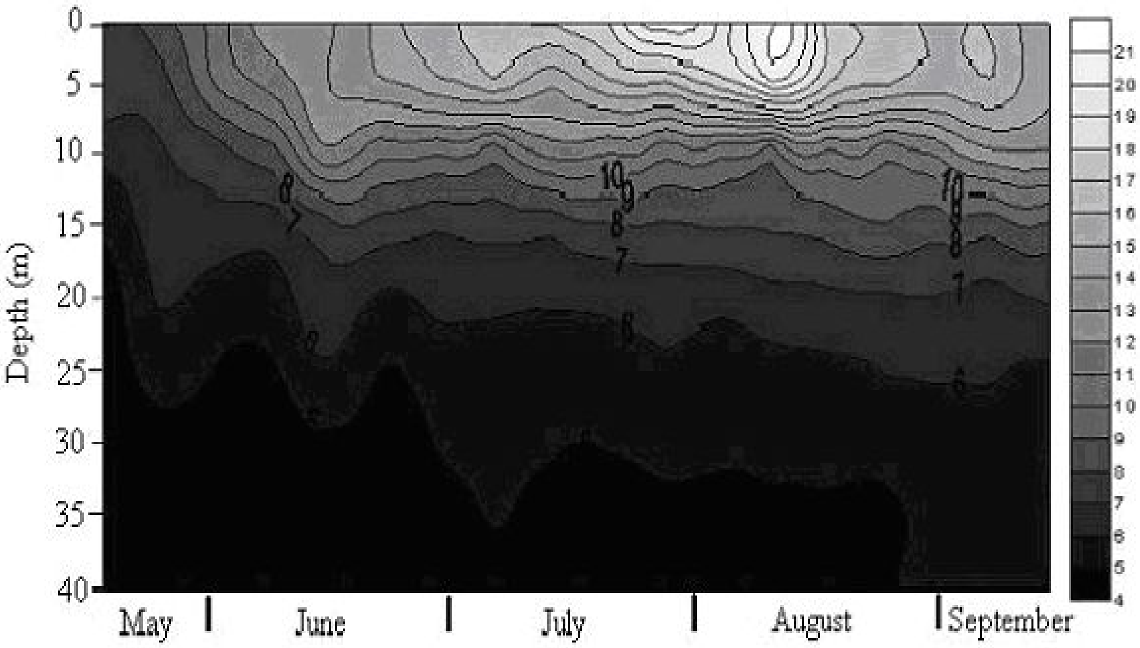

Figure 8. Distribution of temperature in epi- and metalimnion in Lake Pääjärvi during the summer stratification of the year 2004.

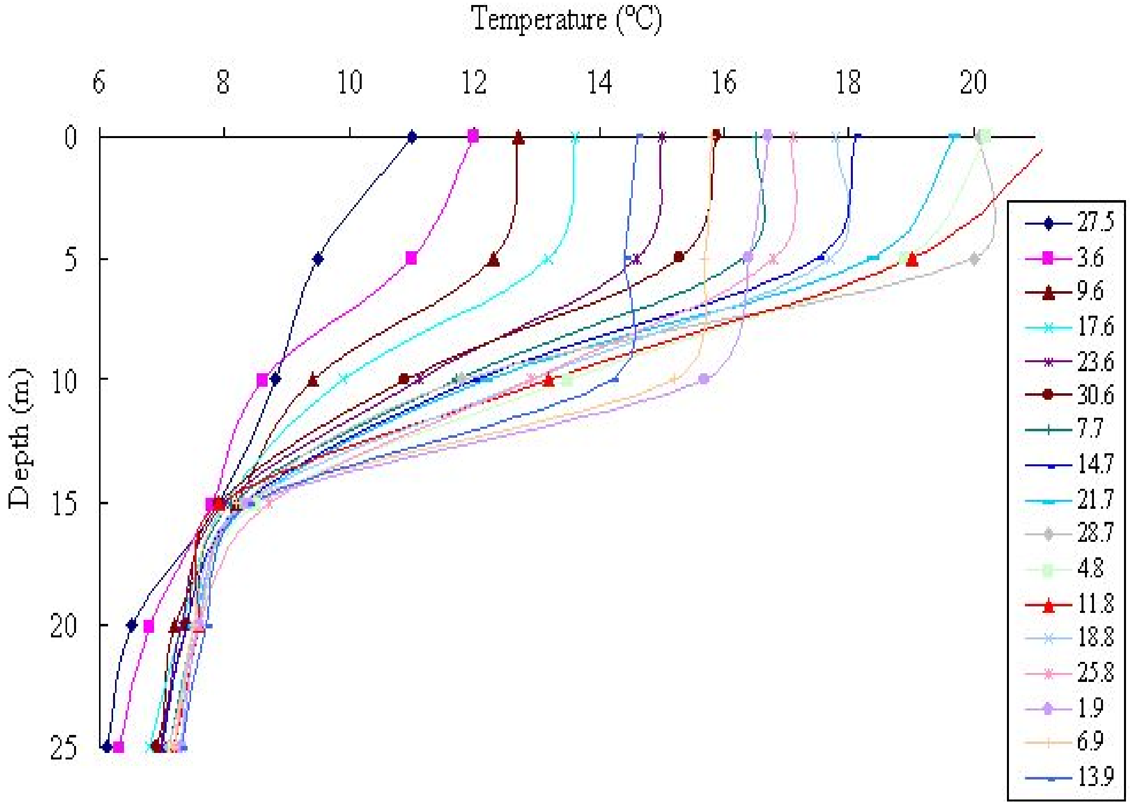

Figure 9. Vertical distributions of temperature at weekly intervals in Lake Ormajärvi during the summer stratification of the year 2004.

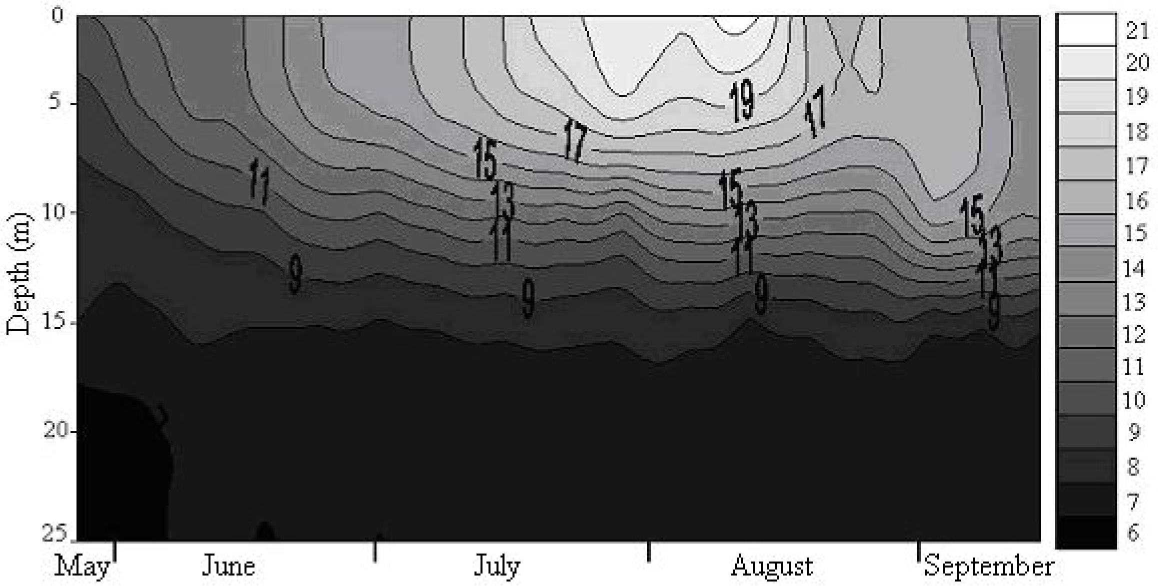

Figure 10. Distribution of temperature in Lake Ormajärvi during the summer stratification of the year 2004.

4.2.2 Hypolimnion

In Lake Pääjärvi the hypolimnion was below 25 to 30 m depending on the depth of thermocline during the course of the summer. In Lake Pääjärvi hypolimnetic temperatures remained low, between 4 and 5 ˚C, during the whole stratification period (Fig. 11). Water near the bottom was slightly colder than water masses at upper layers. In 30 to 50 m layer the temperature differences between different depths were greater than the differences between greater depths in 50 to 75 m, which can be seen from different angles of temperature curves (Figs. 11 and 12). Water masses from 40 to 75 m warmed relatively little, 0.7 to 0.9 ˚C during the stratification period, whereas from 30 to 40 m the respective warming was over 1 ˚C. While water at shallower depths (from 25 to 40 m) started cooling, the water below 50 m continued warming to the end of the sampling period of 14th of September. At the depth of 75 m temperature was notably higher than in the overlying depths throughout the stratification period. The systematically higher temperature at 60 m compared to depths below and above it, are probably unrealistic and due to calibration of the temperature logger. After early July there was a clear shoulder in the vertical distribution of temperature at the depth of 40 m, which separated the upper hypolimnion with high temperature gradients from the deep hypolimnion, where the changes in temperature between different depths were small (Fig. 12).

During the sampling period warming of water was rather constant, but on the top of this trend there were clear periodical oscillations (Figs. 13 and 14). The peaks of higher temperature were generally of short duration (8-10 hours, median of the half maximum width of the 10 most distinct peaks at the depths of 30 and 50 m). The period of internal seiches calculated as a median of the interval between the 20 most distinctive adjacent peaks at the depth of 30 m during June and July was 14 hours (Fig. 13). The one and three knot periods of internal seiches in Lake Pääjärvi calculated from Merian's equation (Hutchinson 1957) for early stratification (late May) were 5.0 and 1.7 hours, whereas during the stable stratification in July the periods were 1.3 and 0.4 hours, respectively.

The highest temperature changes occurred under the metalimnion, where oscillations of > 1 ˚C between adjacent days were found (Fig. 13). The range of variation in temperature decreased as depth increased, and at 50 m temperature changes were at most

0.3 ˚C. After June, along with strengthening stratification, oscillations in temperature in the hypolimnion started to slow down, and periods of rather steady temperatures were found during the late summer. From late July to mid August and late August to early September clear periods of steady temperature existed (Figs. 13 and 14). This pattern was clear in the whole hypolimnion, but especially in the deepest part, where oscillations were smaller. When compared these to the air temperatures, these periods in late July and in late August to early September coincided with similarly small temperature changes in air temperature (Fig. 5). In mid July and in early and late August drop in temperature was evident above 45 m (Fig. 12).

Compared to warming at the first week of June and the end half of the stratification period, warming in the last half of May was rapid. Another relatively rapid hypolimnetic warming period was between 8-15th of June (Fig. 11). Temperature increase was highest at 18-25th of May in 30 m, almost 0.4 ˚C week^{-1}, but in early June there was actually a decrease in temperature, ca. 0.1 ˚C week^{-1} (Fig. 15). From 18th of May temperature increase at depths below 55 m was > 0.1 ˚C week^{-1} till the mid June when temperature increase dropped to 0.05-0.08 ˚C week^{-1} (Fig. 16). This pattern agrees well with clear warming periods of air temperatures in late May and early June with a sudden colder period in the turn of May to June (Fig. 5). However, wind velocities in late May were not nearly as high as in early June, and especially during the stormy second week of June (personal observation), when also period of high temperature increase can be seen in deeper part of hypolimnion. In early summer hypolimnetic temperature increase was most rapid in the upper layers, but also the variation was highest (Fig. 15). In the middle of the summer and in the early autumn highest fluctuations in temperature were again found from the upper part of the hypolimnion near the thermocline. Increase in temperature of the deep hypolimnion stayed at the level 0.04-0.07 ˚C week^{-1} at the end of June and early July, after which it dropped to near zero towards the early August. In mid August temperatures in depths under 55 m increased seemingly faster than at the early and late part of August (Fig. 16), related to the hot weather period. Periods of high temperature increase occurred at late May, mid June, at the intercept of June to July, late July, mid August and at the end of August. During those periods temperature increase was clearly over 0.2 ˚C week^{-1} at 30 and 35 m, whereas it was < 0.1 ˚C week^{-1} at higher depths (Figs. 15 and 16). Temperature increase rate decreased further until the end of the summer. The change from high temperature increase rate to slower one could also be seen in the lower part of the hypolimnion, in which the amplitude of temperature increase rate was smaller (Fig. 16). The interval between high temperature increase rate periods was ca. four weeks at the beginning of the summer, and decreased down to two to three weeks towards the end of the stratification period (Figs. 15 and 16). Weekly temperature increase was clearly higher at the early part of the summer compared to the later part from mid July to mid September, and this trend was rather similar in both the upper and lower hypolimnion. The amplitude of the variation in temperature increase rate did not seem to change much in the course of the summer.

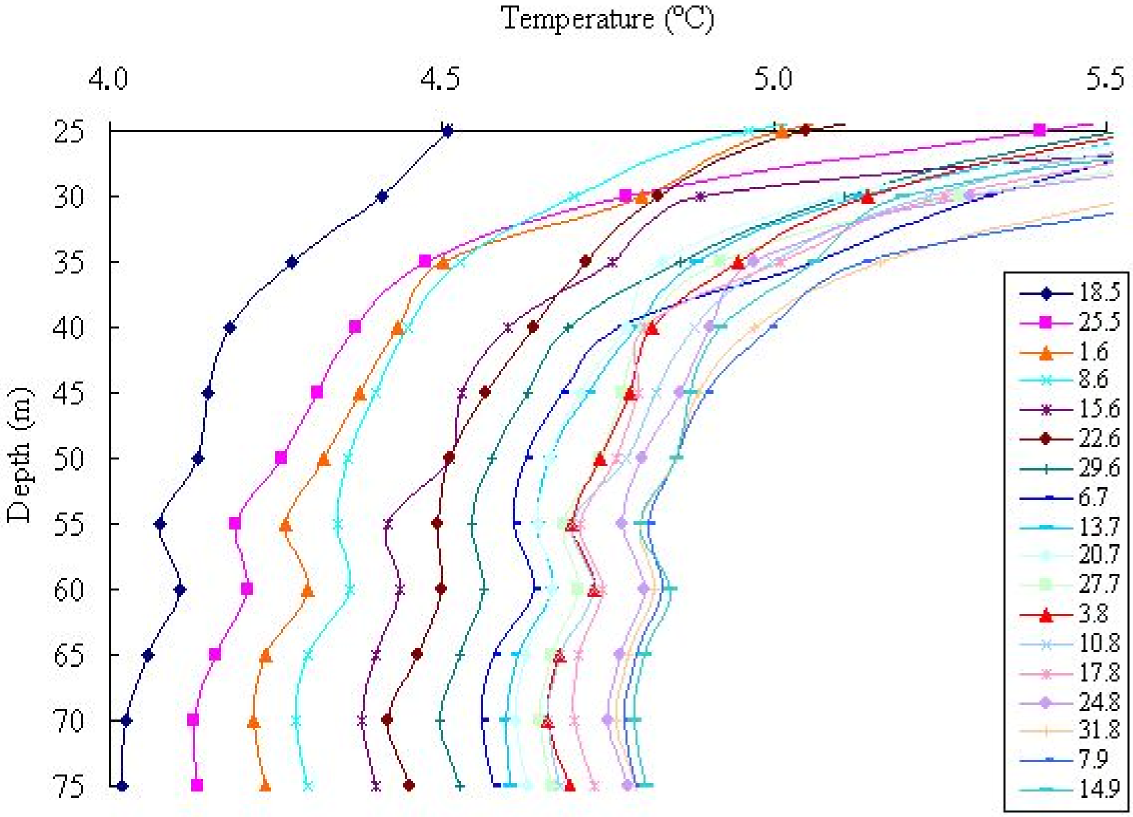

Figure 11. Vertical distributions of temperature at weekly intervals in the hypolimnion of Lake Pääjärvi during the summer stratification of the year 2004.

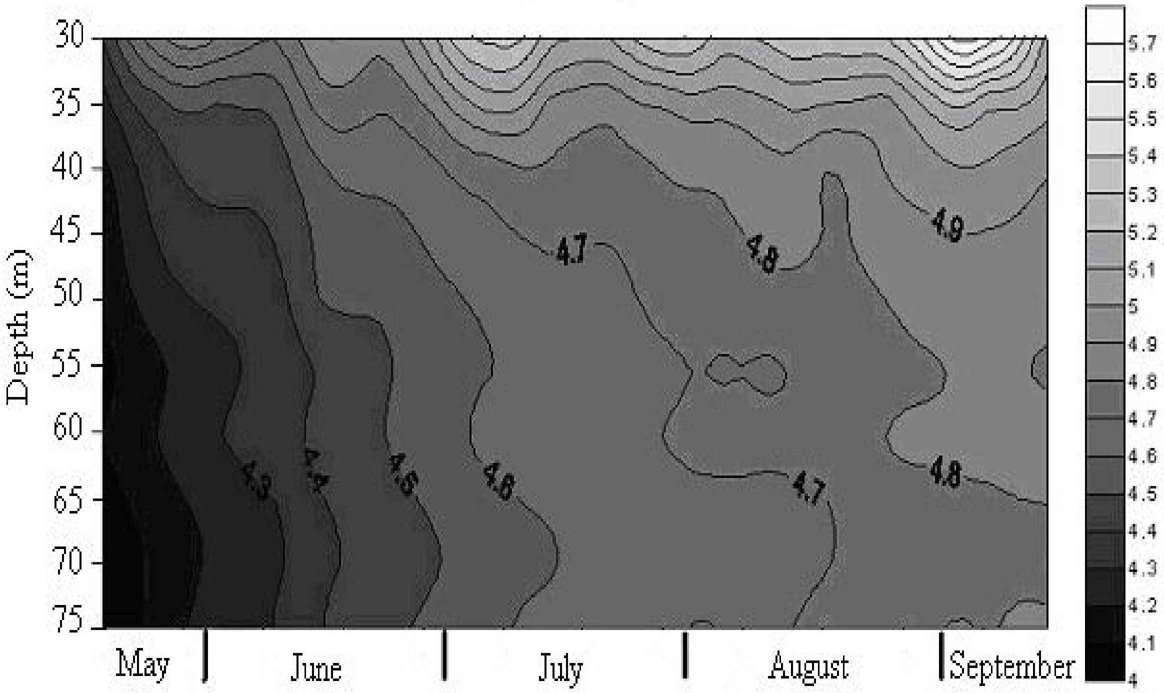

Figure 12. Distribution of temperature in the hypolimnion of Lake Pääjärvi during the summer stratification of the year 2004.

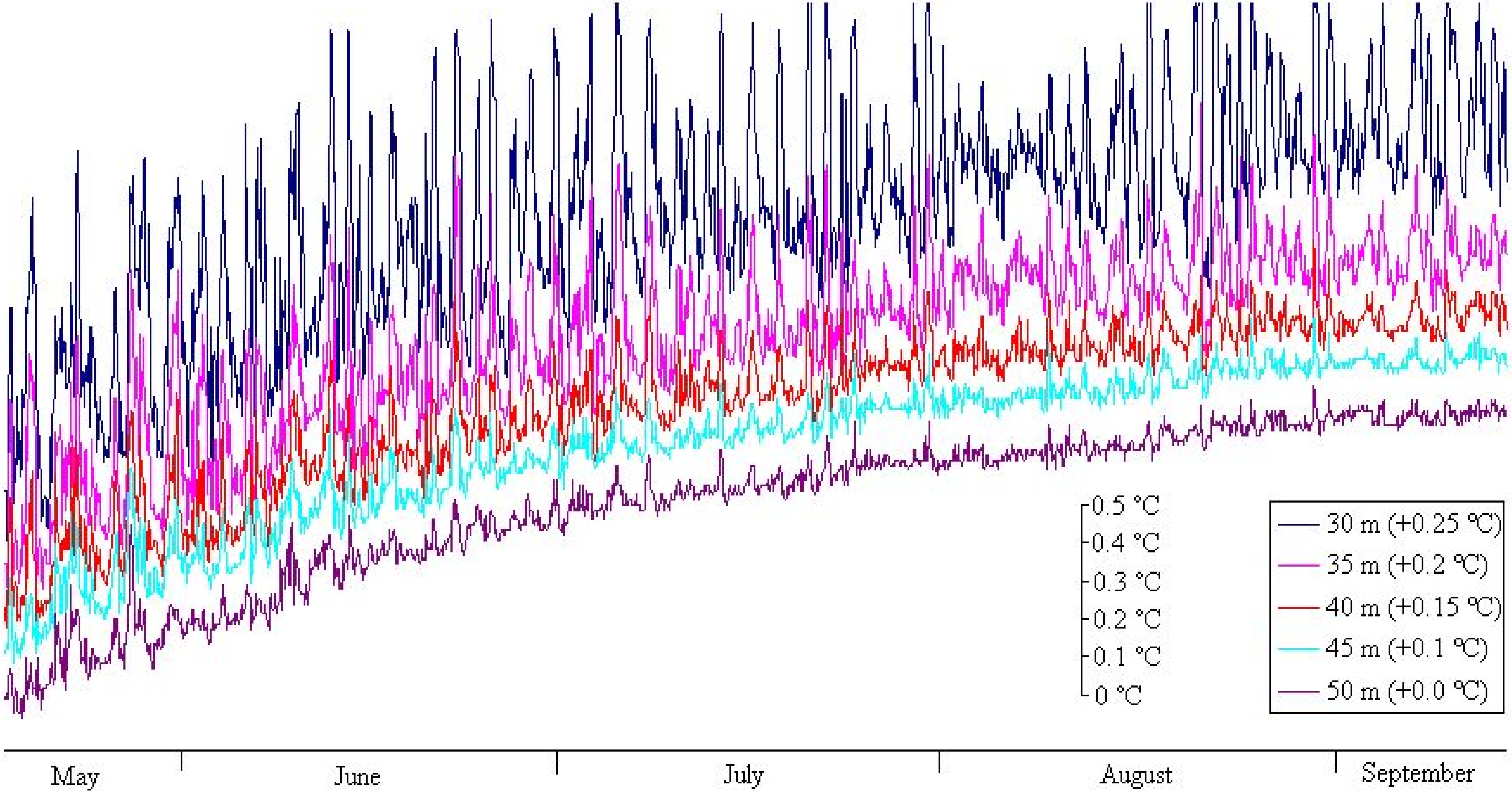

Figure 13. Distribution of temperature in the upper hypolimnion of Lake Pääjärvi during the summer stratification of the year 2004, measured with two-hour intervals. For clarity constants are added to the graphs.

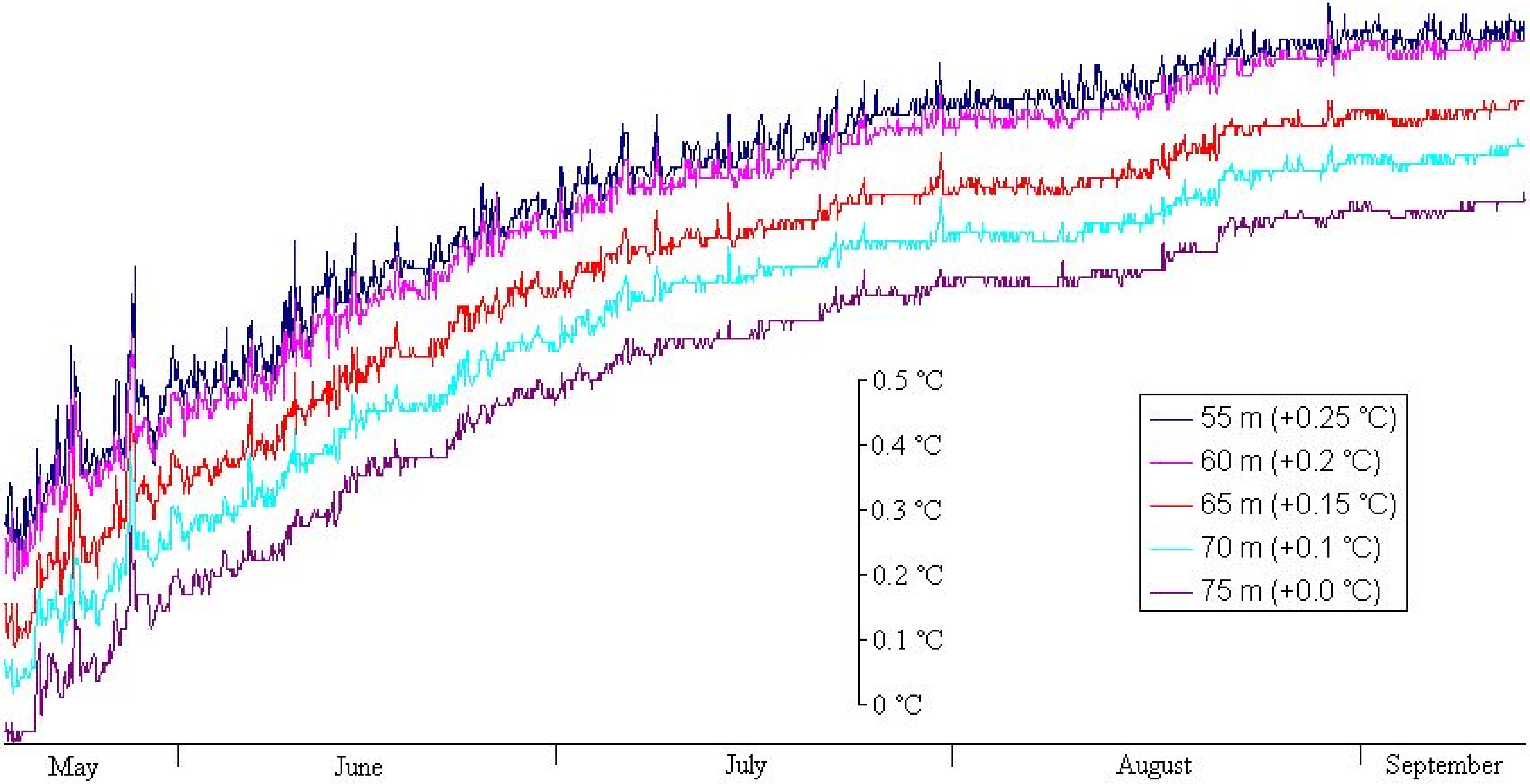

Figure 14. Distribution of temperature in the deep hypolimnion of Lake Pääjärvi during the summer stratification of the year 2004, measured in two-hour intervals. For clarity constants are added to the graph.

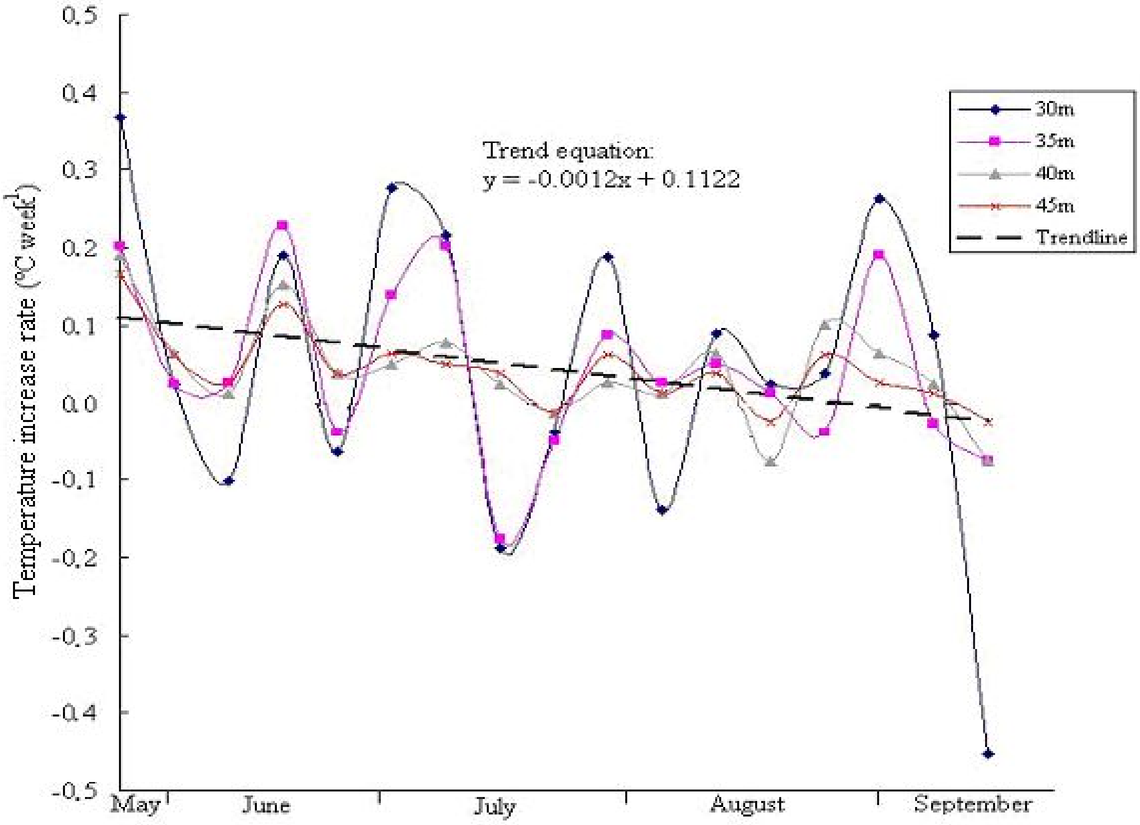

Figure 15. Temperature increase rates in different depths in the upper hypolimnion of Lake Pääjärvi during the summer stratification of the year 2004. The trend line is calculated from the mean values of different sampling dates.

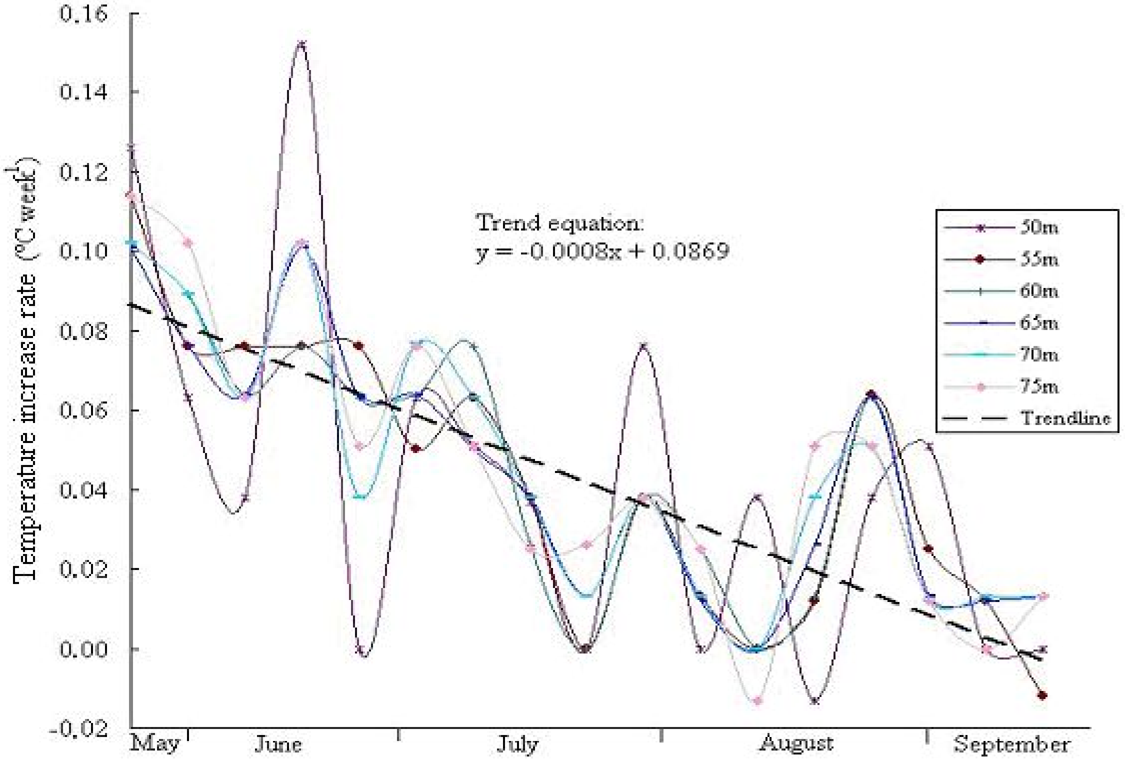

Figure 16. Temperature increase rates in different depths in the deep hypolimnion of Lake Pääjärvi during the summer stratification of the year 2004. The trend line is calculated from the mean values of different sampling dates.

In Lake Ormajärvi the hypolimnion was below 10 to 15 m. In Lake Ormajärvi hypolimnetic temperatures were significantly higher than in Lake Pääjärvi, between 6.1 and 8.5 ˚C during the stratification period, but in the same depth region from 15-25 m temperatures matched quite well (Figs. 7 and 17). Thus, after spring circulation temperature in the hypolimnion was significantly higher than the temperature of maximum density of 4 ˚C. Warming of water masses in 17 to 25 m layer was rapid during the two weeks in the beginning of stratification, > 0.5 ˚C week^{-1} in 25 m depth and ca. 0.4 ˚C in 20 m depth (Figs. 17 and 18) and the temperature differences between upper and lower hypolimnion were large compared to the end of the sampling period. Later warming slowed down to clearly under 0.1 ˚C week^{-1}. Although the warming of hypolimnetic water slowed down towards the end of the stratification period, continuous heating was still evident, whereas in the same depths of Lake Pääjärvi slight cooling could be seen (Figs. 7 and 17). At the end of August there was a clear drop in temperature of the whole hypolimnion (Fig. 18). This followed the cooling of the epilimnion with a short time lag. At the beginning of September fairly similar situation occurred.

At the early summer temperature increase rates in hypolimnion ranged from relatively high 0.7 ˚C week^{-1} down to 0.2 ˚C week^{-1} (Fig. 19). As in Lake Pääjärvi, temperatures in hypolimnion increased most rapidly from late May to early June. Later, from late June to mid August there was a period of very slow temperature increase, clearly < 0.2 ˚C week^{-1}. Temperature in the epilimnion had already started to decrease in early August at the rate of 0.8-> 3 ˚C week^{-1}, but hypolimnetic temperatures increased even during the last week of sampling in September (Fig. 19). The intervals between periods of rapid warming, and on the other hand the intervals between periods of slow temperature increase lasted about two weeks throughout the sampling period in the hypolimnion. The fluctuations in the hypolimnion were highest near the thermocline, damping towards the bottom.

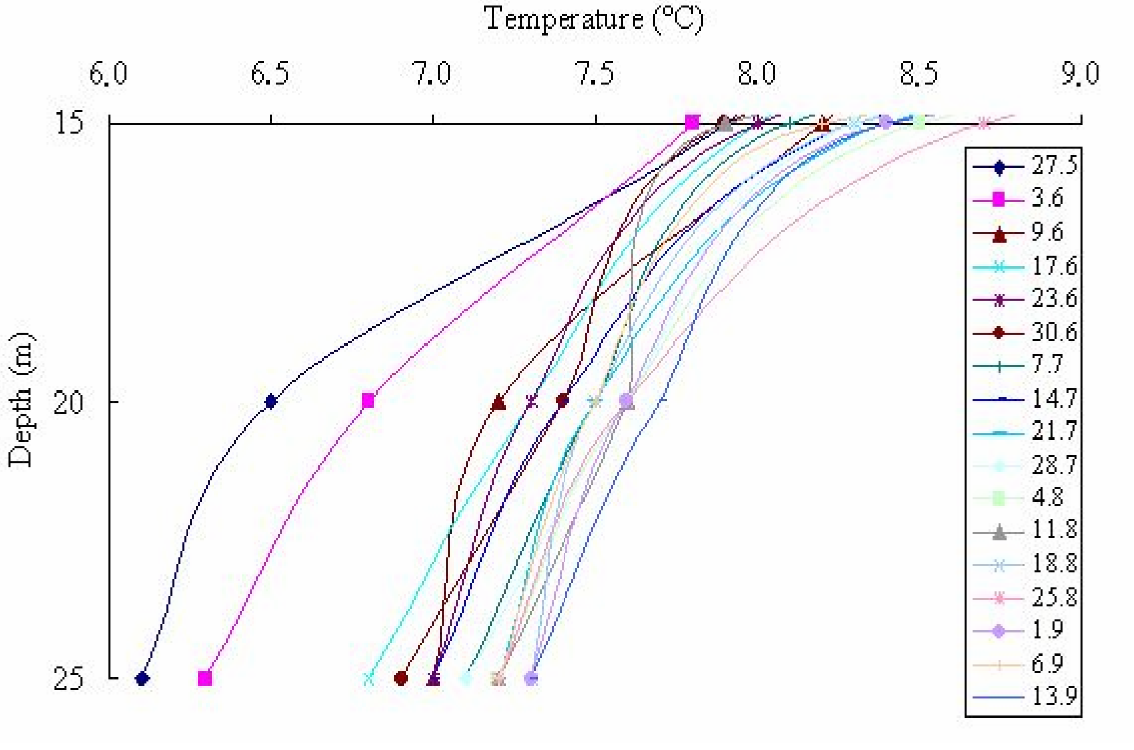

Figure 17. Vertical distributions of temperature at weekly intervals in the hypolimnion of Lake Ormajärvi during the summer stratification of the year 2004.

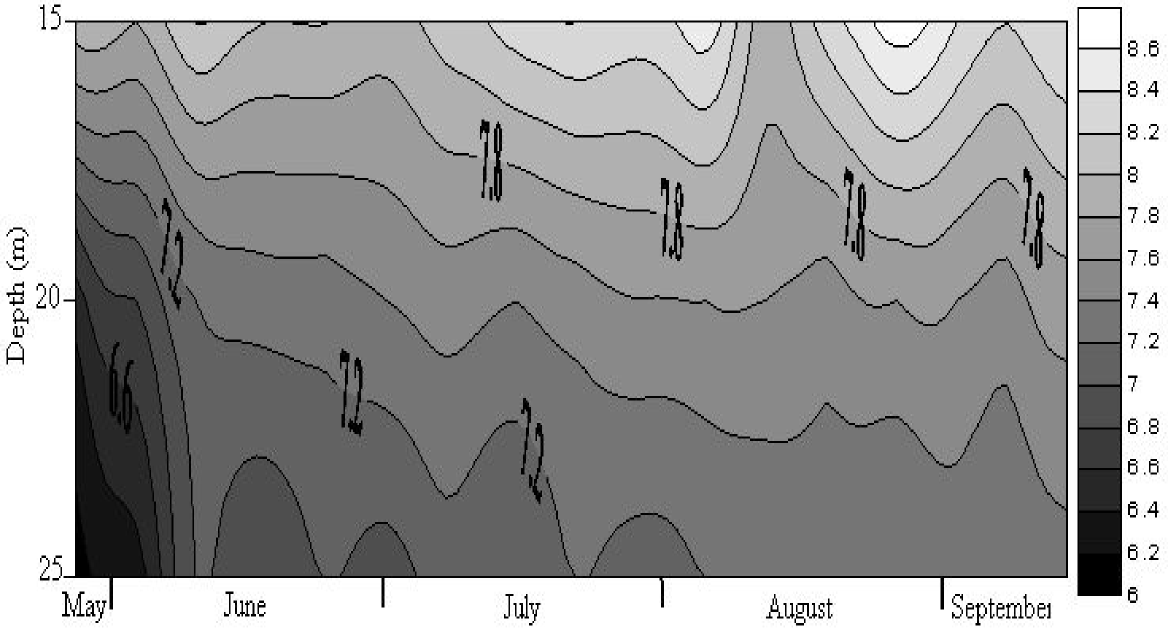

Figure 18. Distribution of temperature in the hypolimnion of Lake Ormajärvi during the summer stratification of the year 2004.

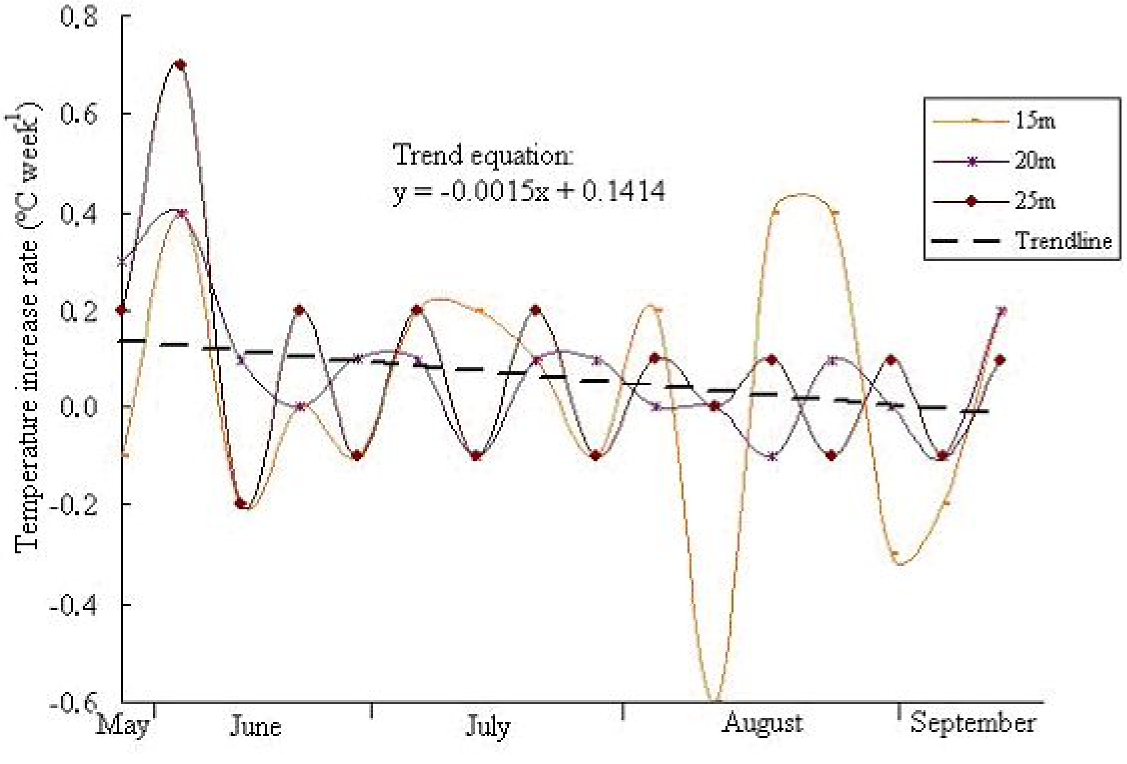

Figure 19. Temperature increase rates in the hypolimnion of Lake Ormajärvi during the summer stratification of the year 2004. The trend line is calculated from the mean values of different sampling dates.

4.2.3 Sediment temperature

Because no sediment temperature data was available from Lake Pääjärvi in the year 2004, the values from the year 2005 are used to have some idea of the heat flow between water and the sediment. In early May 2005, at the depth of 20 m sediment temperature of

Lake Pääjärvi was ca. 0.1 ˚C lower than that of the overlying water (Fig. 20 a). In 40 m depth the respective difference was even higher, ca. 0.2 ˚C (Fig. 20 b).

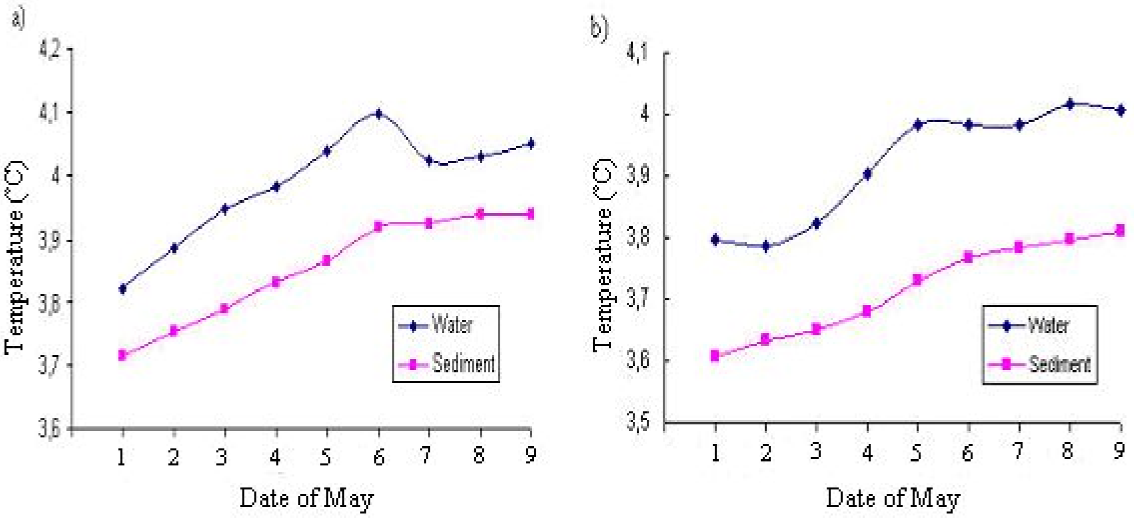

Figure 20. Temperatures of sediment (ca. 15 cm inside the sediment) and overlying water in 20 (a) and 40 m (b) sites in Lake Pääjärvi from 1st to 9th of May of the year 2005.

4.3 Dissolved oxygen

4.3.1 Lake Pääjärvi

From the middle of May the concentration of dissolved oxygen remained high and quite constant in the whole water column of Lake Pääjärvi until the early June (Fig. 21), when stable stratification was established (Fig. 7). Then oxygen concentration in epilimnion decreased in parallel with the increase in temperature (Figs. 7 and 21). The same was found also in the metalimnion (5-20 m), where oxygen minimum became clearly evident after early July (Fig. 22). The oxygen minimum zone was from five to 10 m at the early stage and moved deeper, to 10-25 m during the late summer. Minimum concentrations of dissolved oxygen in different sampling occasions were found in the upper epilimnion except after the middle of May when oxygen minimum was near the bottom at 75 m. Same kind of borderline, which was seen in temperature gradients in 40 m (Fig. 12) became evident in oxygen profile after mid July (Fig. 22). Decrease in oxygen concentration seemed to be lowest in that specific depth region during late summer. The changes and fluctuation in oxygen concentration were highest in the epi- and metalimnion throughout the summer. In surface water oxygen saturation ranged from 106 % in the late June to 91 % at the end of the stratification period (Fig. 23). At the beginning of the sampling period oxygen concentration was quite uniform in the whole hypolimnion with 89-90 % saturation (Figs. 21 and 24). Oxygen concentration decreased most rapidly near the bottom, but even in September there was still plenty of oxygen (> 9 mg l^{-1} with over 70 % saturation) available in the deepest part of the lake (Figs. 21 and 24). In the whole hypolimnion oxygen saturation fell below 80 % during the stratification.

During the first week at June a slight increase in oxygen consumption in whole water column occurred, although according to temperature data mixing already decreased due to enforcing stratification. Oxygen consumption in the lower hypolimnion was (ca. 0.15 mg l^{-1} $week^{-1}$), whereas it was lower (< 0.1 mg l^{-1} $week^{-1}$) in upper hypolimnion throughout the stratification period (Fig. 22). However, no significant differences in oxygen consumption rates between depths in hypolimnion were found (Friedman: $\chi^2 = 5.62$, df = 9, P = 0.78).

The linear regression and the initial-final difference methods yielded very similar values (Table 2). Clear increase in oxygen consumption between upper and lower hypolimnion seemed to happen between 45 and 50 m depths (Table 2).

The changes in oxygen concentration in epilimnion are highly related to temperature. Therefore this section only deals with the hypolimnion. Weekly oxygen consumption rates fluctuated generally between 0.05 and 0.25 mg l^{-1}. Temporal variation was highest at the depths of 70 and 75 m, ranging from 0-0.3 mg l^{-1} per week (Fig. 26). When oxygen consumption rates were lowest, oxygen saturation in surface seemed to be highest (Figs. 23, 25 and 26). From July to August (sampling interval of three weeks) and August to September (sampling interval of four weeks) the rates of oxygen consumption were quite similar in the whole water column and no major fluctuations between depths could be found. During the stratification period rate of temperature increase and oxygen consumption were significantly negatively correlated in the lower hypolimnion below 40 m (Table 3), i.e. when warming of the hypolimnion increased, the rate of oxygen consumption decreased. However, warming rate explained only ca. 5 % of the variation of oxygen consumption rate. In fact, in spite of the decrease in warming rate towards the end of the summer, weekly oxygen consumption rates seemed to increase towards the end of the stratification period in the lower hypolimnion (Figs. 16 and 26). Instead, a slightly decreasing trend was seen in the upper hypolimnion (Fig. 25), but no significant correlations in the upper hypolimnion or in single depths were found.

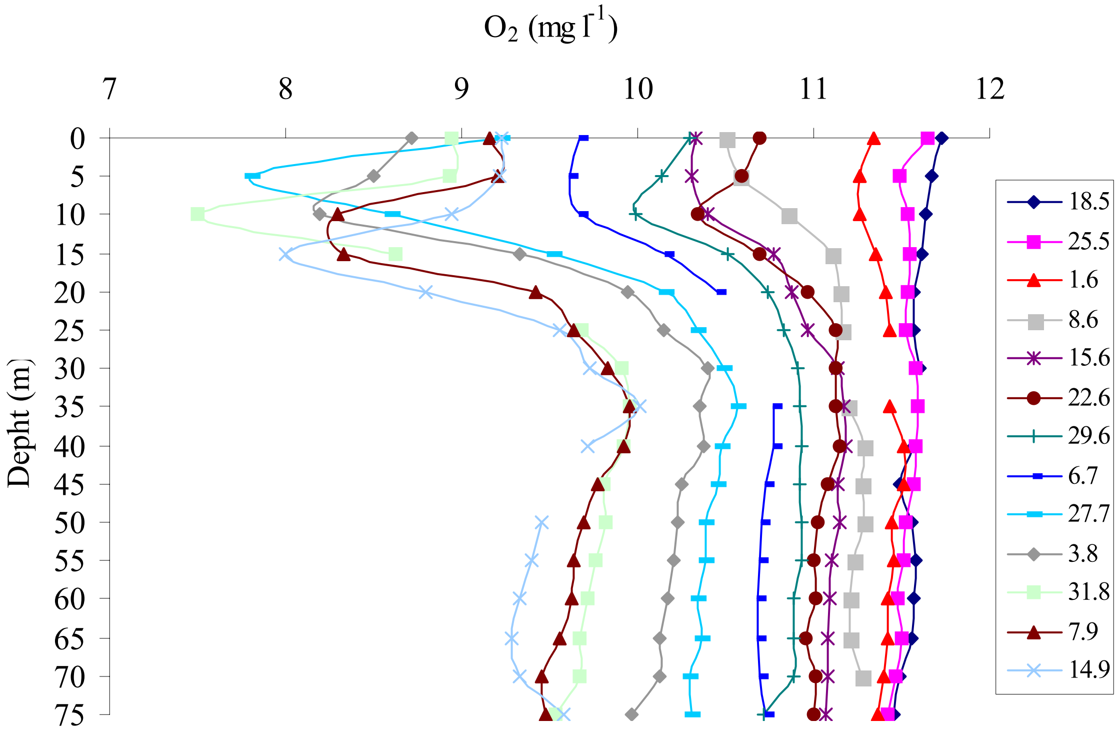

Figure 21. Vertical distributions of dissolved oxygen at different sampling days in water column of Lake Pääjärvi during the summer stratification of the year 2004.

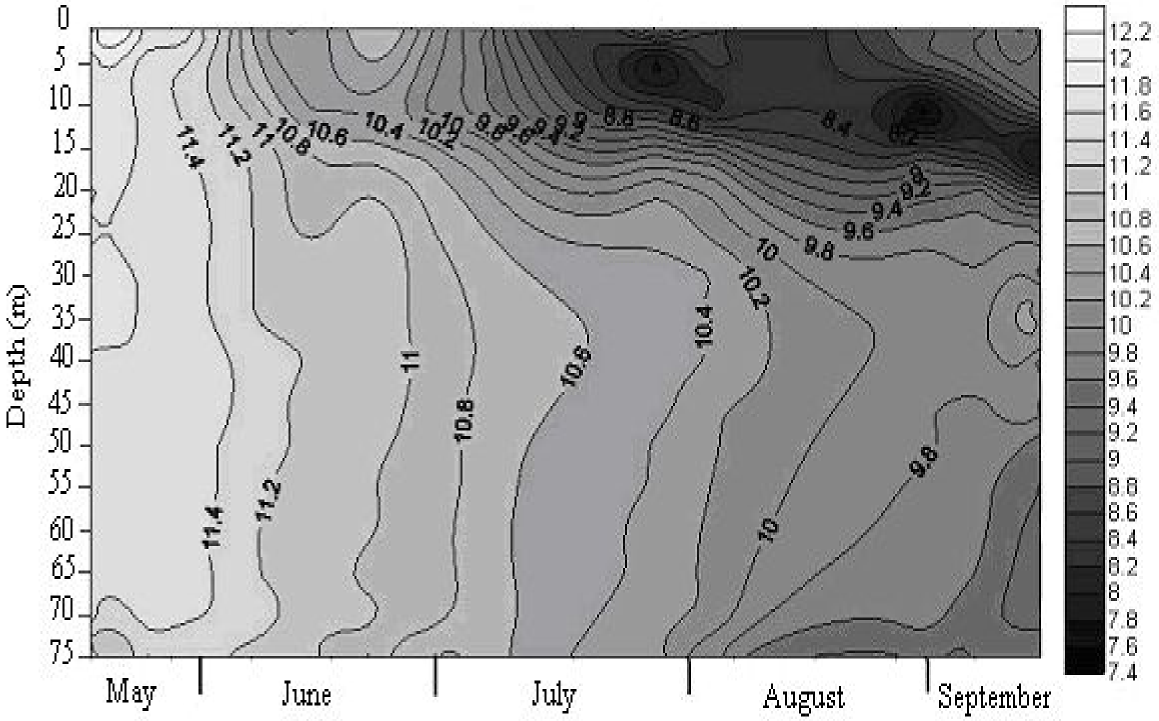

Figure 22. Distribution of dissolved oxygen in water column of Lake Pääjärvi during the summer stratification of the year 2004.

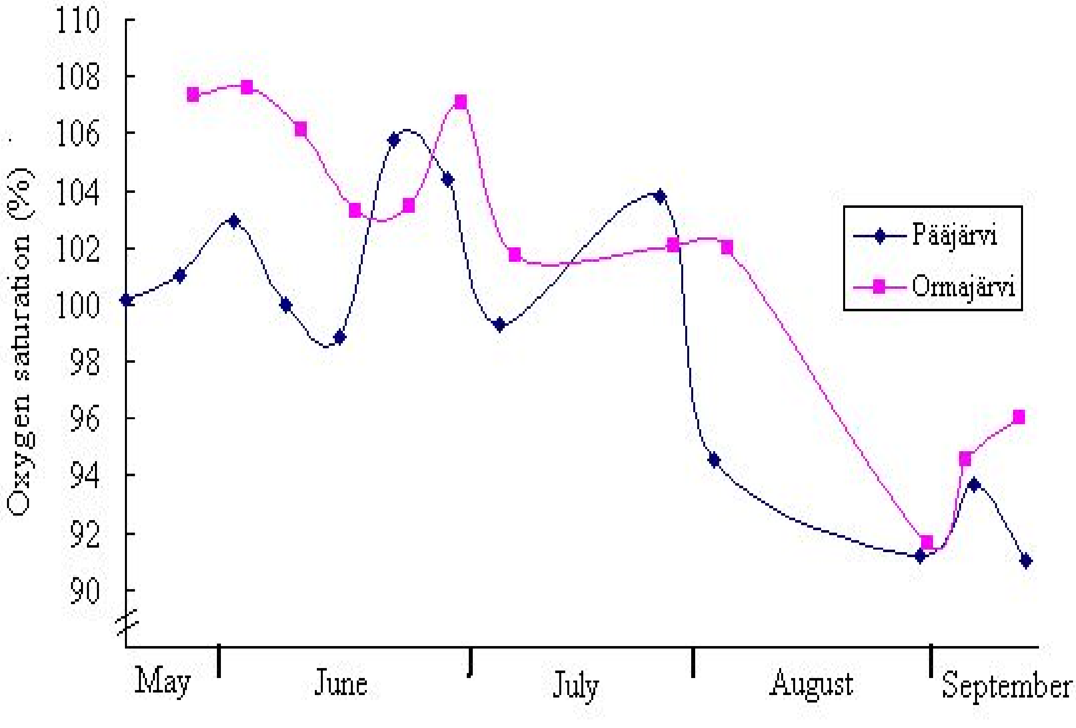

Figure 23. Oxygen saturation time series at the surface of Lake Pääjärvi and Lake Ormajärvi during the summer stratification of the year 2004.

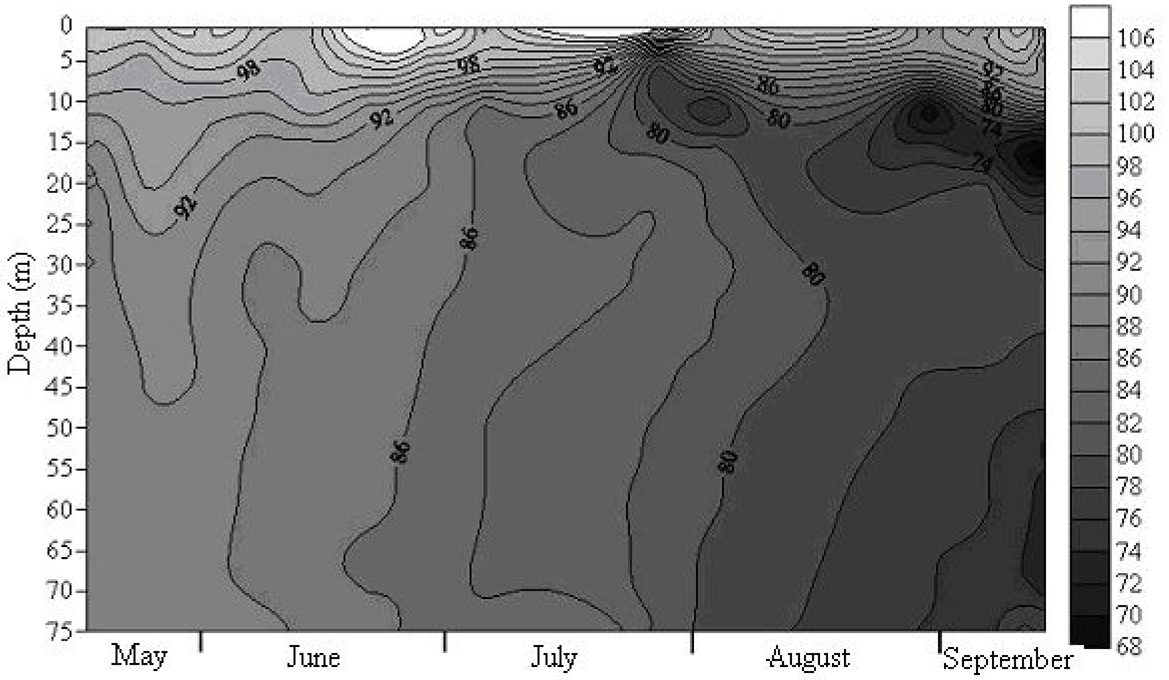

Figure 24. Oxygen saturation in Lake Pääjärvi during the summer stratification of the year 2004.

Table 2. Hypolimnetic oxygen consumption in different depths in Lake Pääjärvi during the sampling period of the year 2004, calculated with linear regression method with all of the values used and at the difference between the values at the beginning and at the end of the sampling period.

Depth (m)	Linear regression (mg l^{-1})	Difference (mg l^{-1})
30	1.89	1.88
35	1.89	1.58
40	1.89	1.86
45	1.89	1.90
50	2.27	2.11
55	2.27	2.18
60	2.27	2.24
65	2.27	2.27
70	2.27	2.16
75	2.27	1.87

Table 3. Spearman's correlations between temperature increase rates and oxygen consumption rates in differents depths.

Depth (m)	N	Spearman's ρ	P	R^2
30-75	111	-0.127	0.185	0.016
30-50	53	-0.022	0.877	< 0.001
40-75	92	-0.269	0.009**	0.072
50-75	70	-0.345	0.003**	0.119

** Correlation is significant at the 0.01 level (2-tailed).

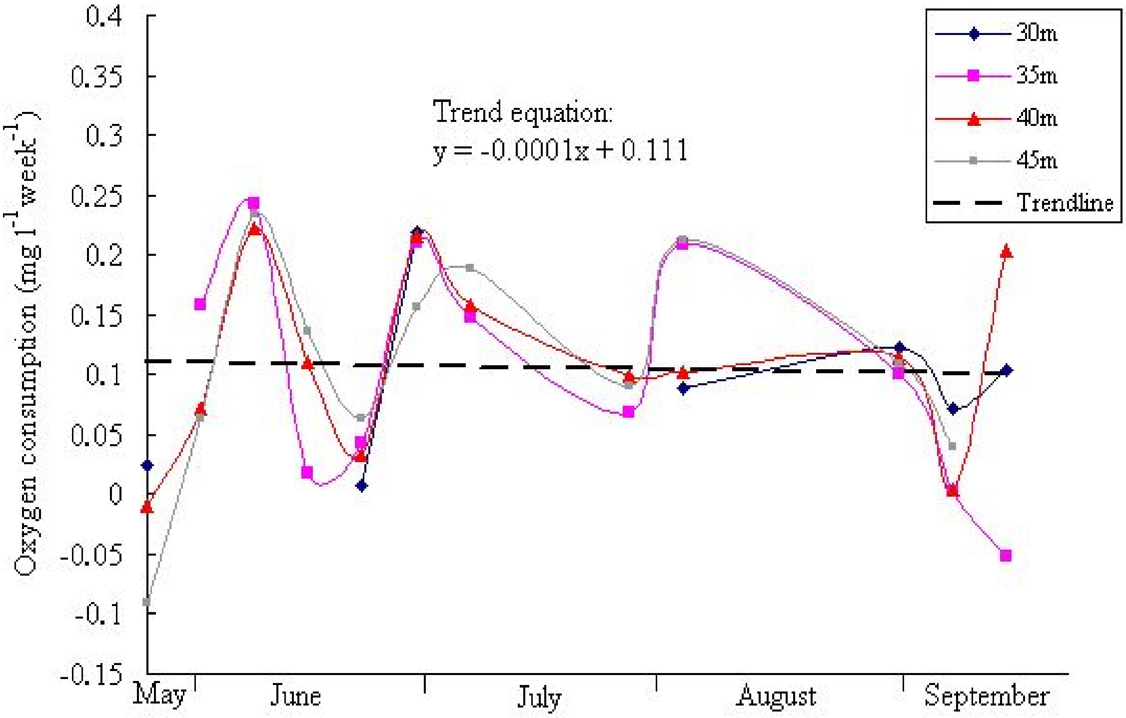

Figure 25. Weekly oxygen consumption in the upper hypolimnion of Lake Pääjärvi during the summer stratification of the year 2004. The trend line is calculated from the mean values of different sampling dates.

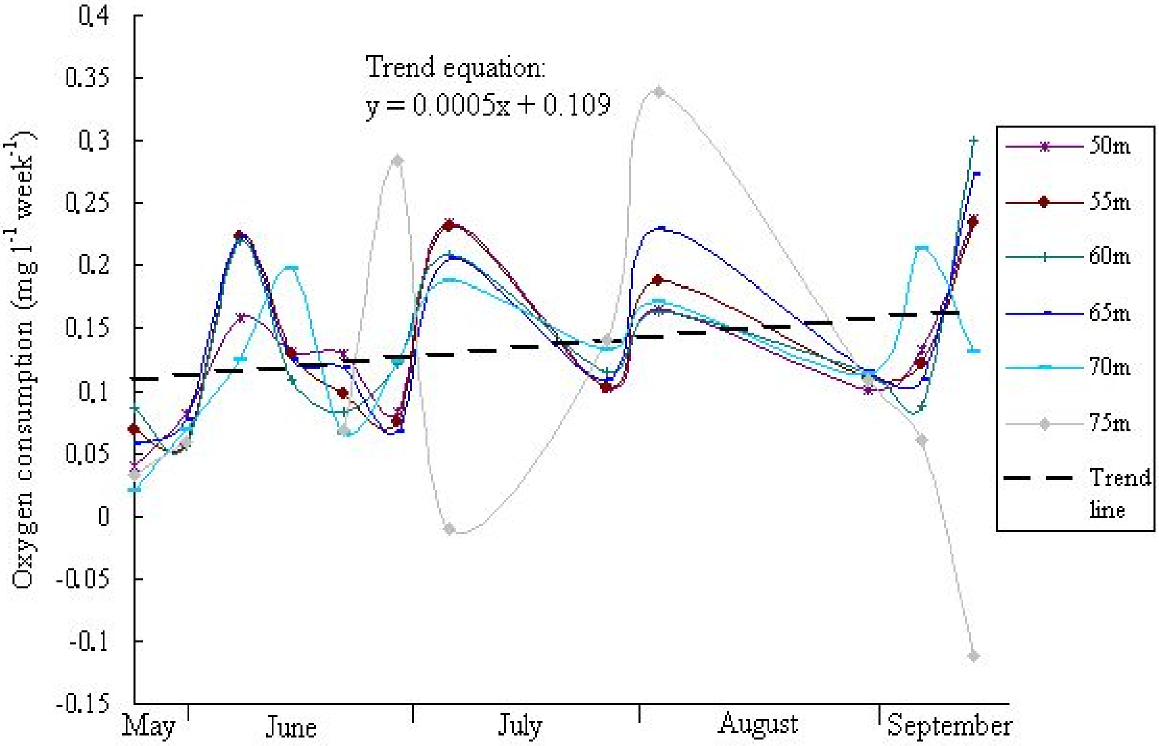

Figure 26. Weekly oxygen consumption in the deep hypolimnion of Lake Pääjärvi during the summer stratification period of the year 2004. The trend line is calculated from the mean values of different sampling dates without 75 m depth.

4.3.2 Lake Ormajärvi

In late May in Lake Ormajärvi differences in dissolved oxygen concentrations between different depths in hypolimnion were small, similar situation found in the differences in water temperature (Figs. 9 and 27). However, the concentrations near the bottom were slightly lower than near the surface, but still nearly 12 mg l^{-1} with 98 % saturation (Fig. 27 and 29). Therefore the stratification of oxygen had not started yet. When stratification of temperature became evident in mid June, oxygen concentration below 8 m decreased rapidly leading to slightly negative heterograde distribution. From early August to early September oxygen concentrations increased in first 10 meters along with decreasing temperature. Since the end of June clear decrease in oxygen concentration (to nearly 6 mg l^{-1}) was observed in depths between 10-15 m (Figs. 27 and 28). Metalimnetic oxygen minimum was fading towards September (Fig. 28), when the lowest concentration of oxygen could be found near the bottom. Oxygen saturation at the surface was highest at late May (108 %) and decreased smoothly to still quite high levels of 94 % at the early September (Fig. 23). Oxygen concentration in hypolimnion decreased throughout the sampling period. At the end of the sampling oxygen concentration near the bottom had decreased to a low level of < 2 mg l^{-1} with only 17 % saturation (Figs. 27 and 29).

In general, hypolimnetic oxygen concentration decreased most rapidly in the deepest water layer (Fig. 28). In early summer oxygen consumption rates ranged from 0.3 to > 1.0 mg l^{-1} week^{-1}, and dropped to < 0.6 mg l^{-1} week^{-1} in late summer (Fig. 30). No significant differences in oxygen consumption rates between depths in the hypolimnion were found (Friedman: $\chi^2 = 0.29$, df = 2, P = 0.87). However, the small number of observation depths below 10 m can mislead the interpretations. Periods of high oxygen consumption rates in hypolimnion occurred in late May, mid June, late July and in the turn of August to September (Fig. 30). The cycle of temperature changes between high increase periods lasted for ca. 2 weeks, whereas no clear pattern in oxygen consumption rates could be seen (Figs. 19 and 30). No significant correlation between temperature increase rates and oxygen consumption rates in hypolimnion were found (Spearman's correlation: n = 27, ρ = 0.037, P = 0.86). Similar to the temperature increase rate (Fig. 19), the oxygen consumption rate in the hypolimnion slowed down towards the end of stratification period (Fig. 30).

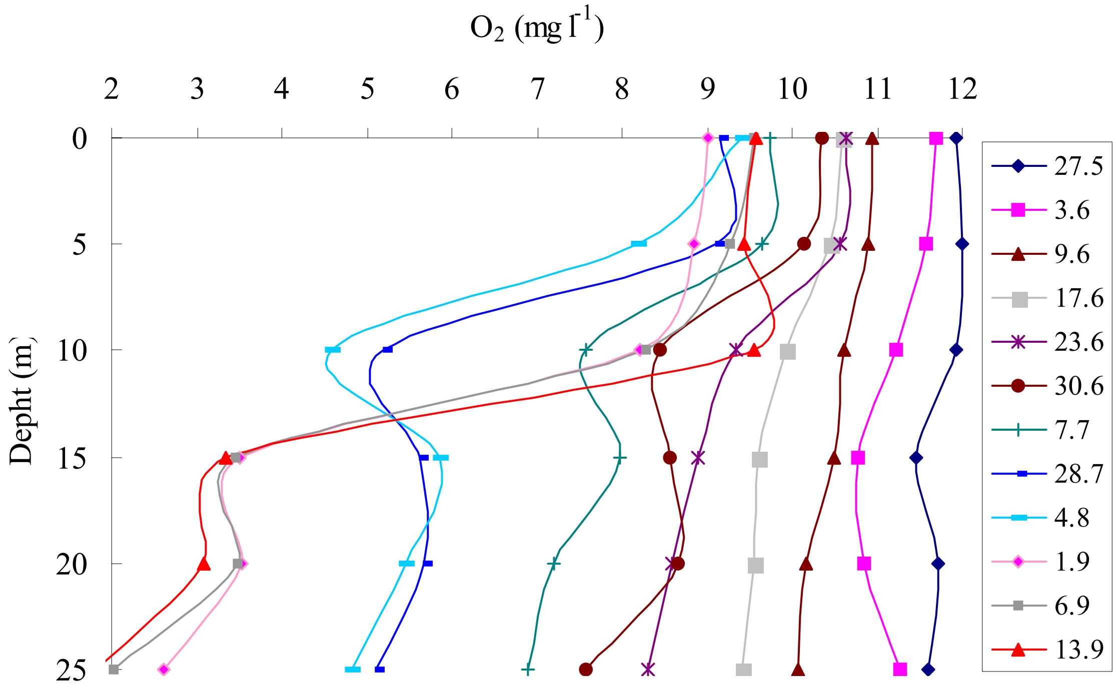

Figure 27. Vertical distributions of dissolved oxygen at different sampling days in water column of Lake Ormajärvi during the summer stratification of the year 2004.

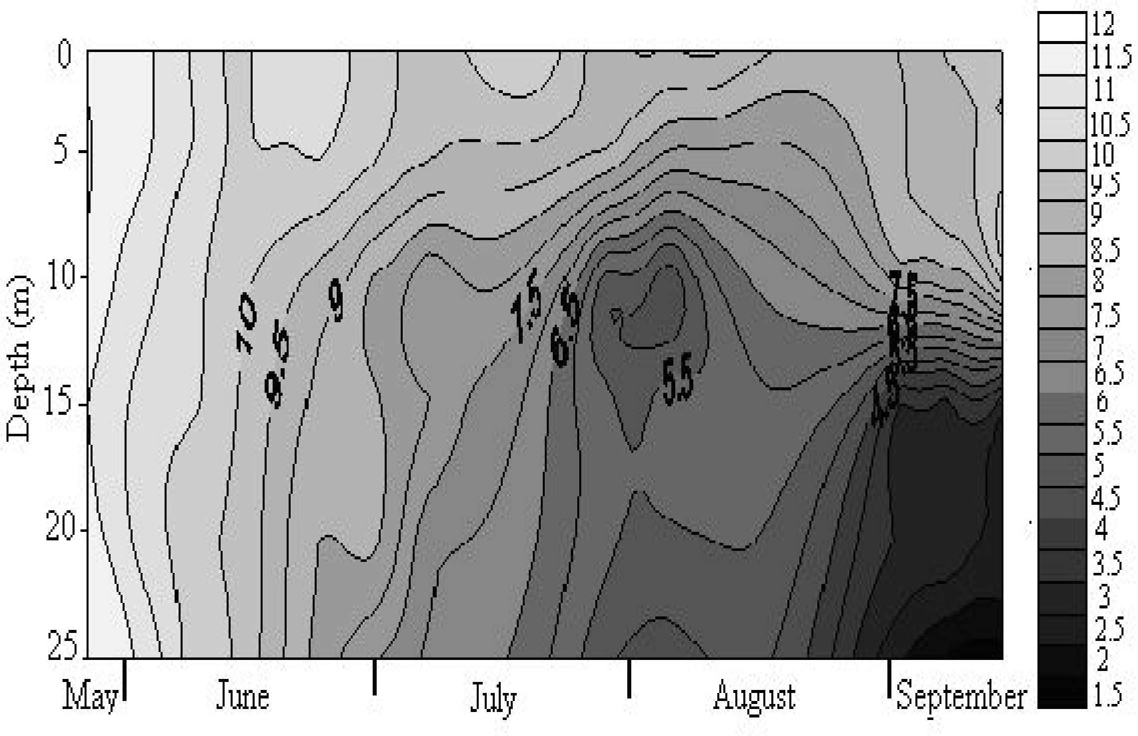

Figure 28. Distribution of dissolved oxygen in water column of Lake Ormajärvi during the summer stratification of the year 2004.

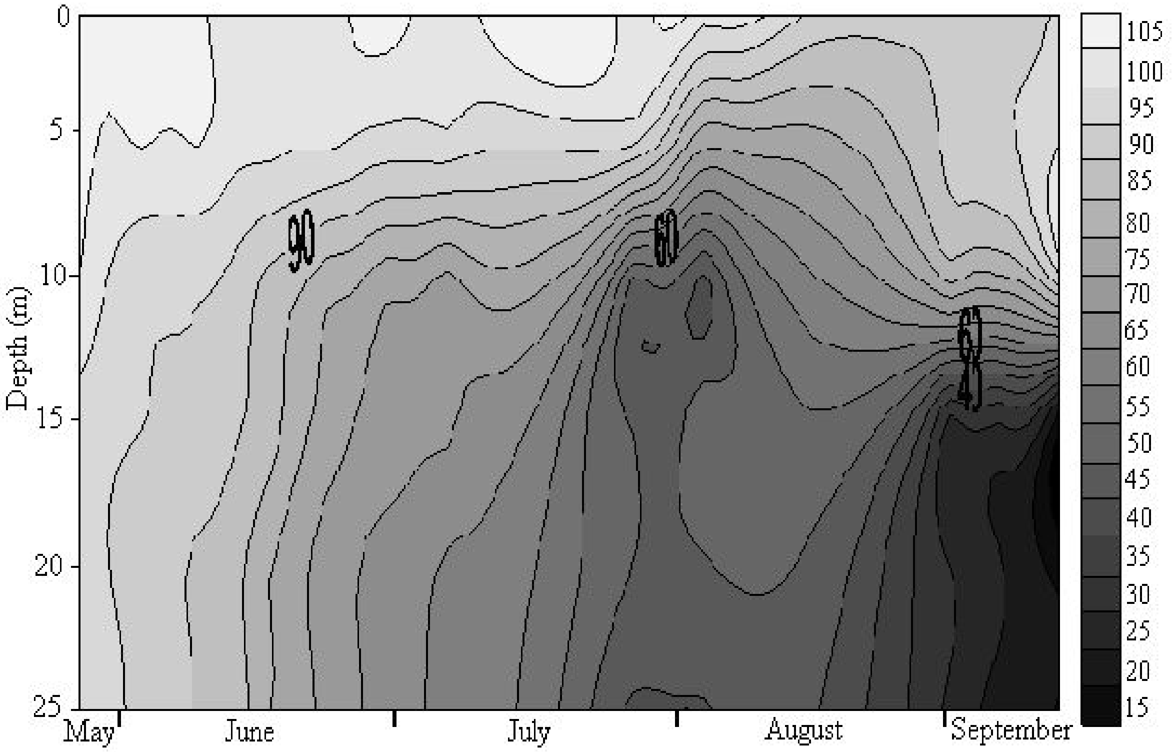

Figure 29. Oxygen saturation in Lake Ormajärvi during the summer stratification of the year 2004.

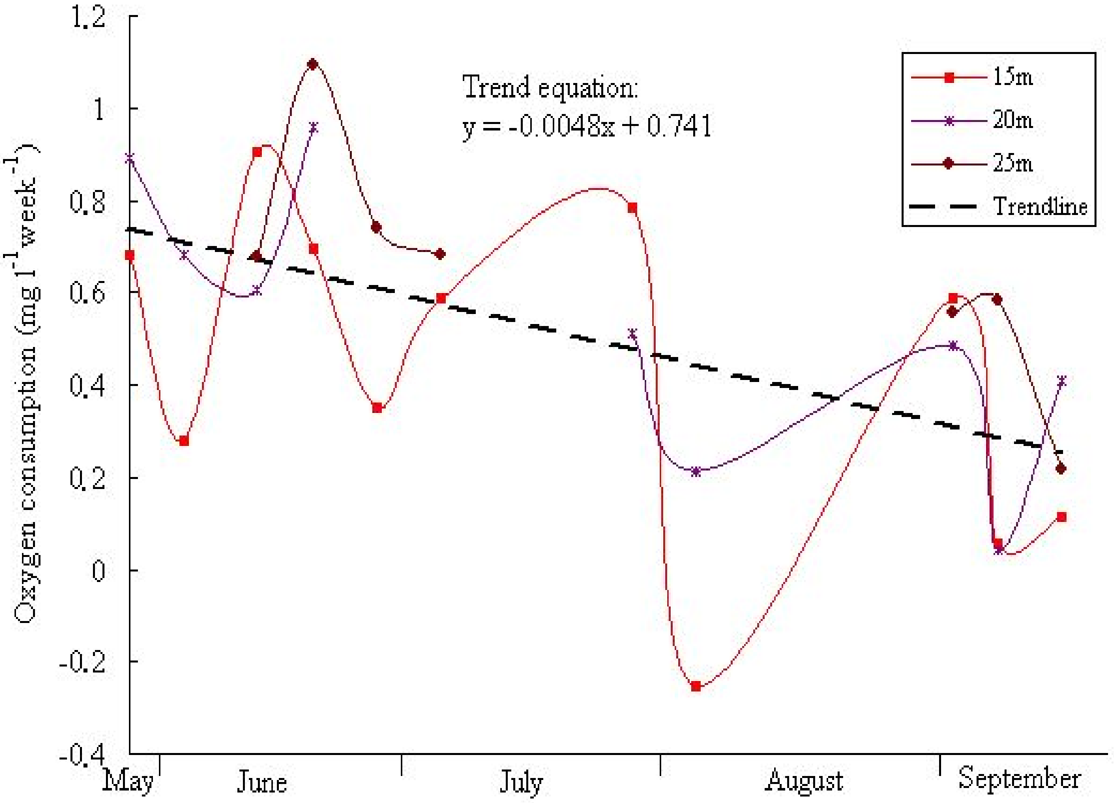

Figure 30. Weekly oxygen consumption in the hypolimnion of Lake Ormajärvi during the summer stratification of the year 2004. The trend line is calculated from the mean values of different sampling dates.

4.4 Dissolved inorganic carbon

In Lake Pääjärvi dissolved inorganic carbon concentrations remained quite low (between 2.9-3.5 mg l^{-1}) near the surface throughout the sampling period and no major fluctuations could be found (Fig. 31). After the end of spring circulation in mid June hypolimnetic dissolved inorganic carbon concentrations increased quite steadily throughout the summer (Figs. 31 and 32), and the highest values were generally found in the deepest water layers. A weak dissolved inorganic carbon maximum at the metalimnion was starting to appear at the end of July in depths around 10-15 m, but moved deeper during September, at 15-20 m (Figs. 31 and 32). This was clearly connected to the metalimnetic oxygen minimum. In each sampling occasion the maximal dissolved inorganic carbon concentration was found in the lower part of the hypolimnion, below 55 m. The increase in dissolved inorganic carbon concentration was slightly higher in lower part of hypolimnion than in upper part, ca. 0.2 and 0.15 mg l^{-1} week^{-1}, respectively (Figs. 31 and 32).

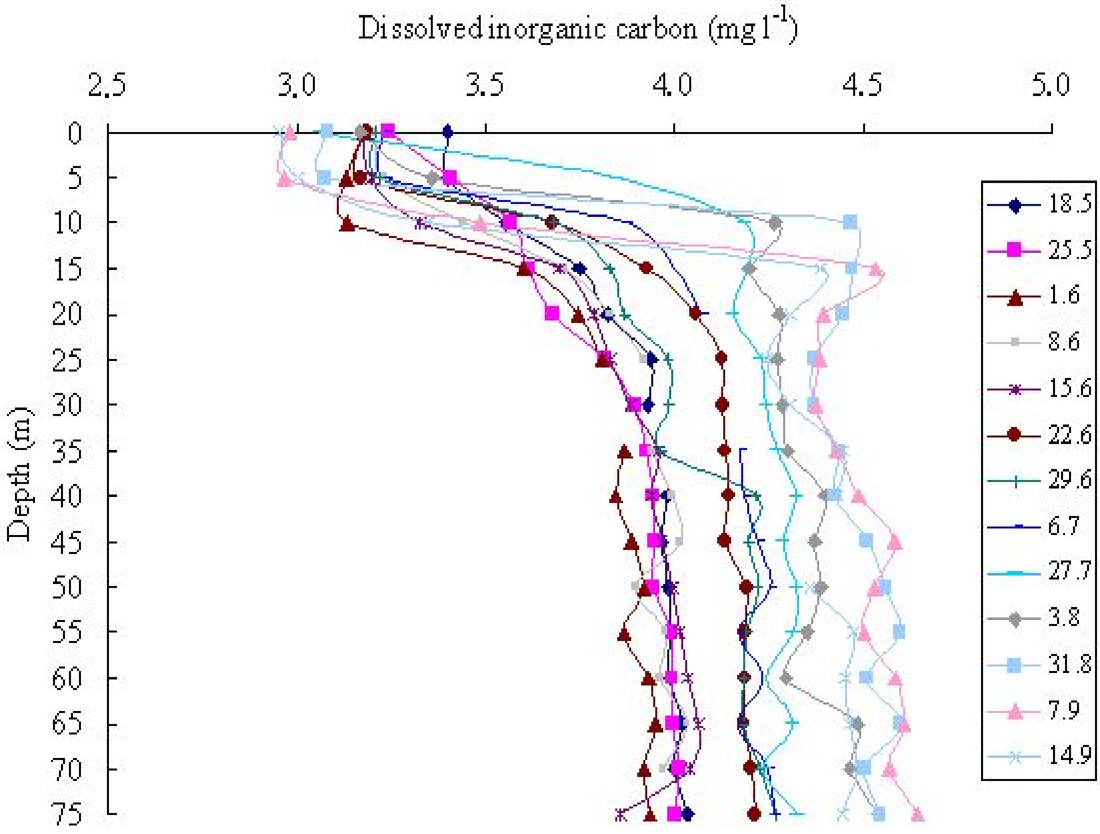

Figure 31. Vertical distributions of dissolved inorganic carbon at different sampling days in water column in Lake Pääjärvi during stratification of the year 2004.

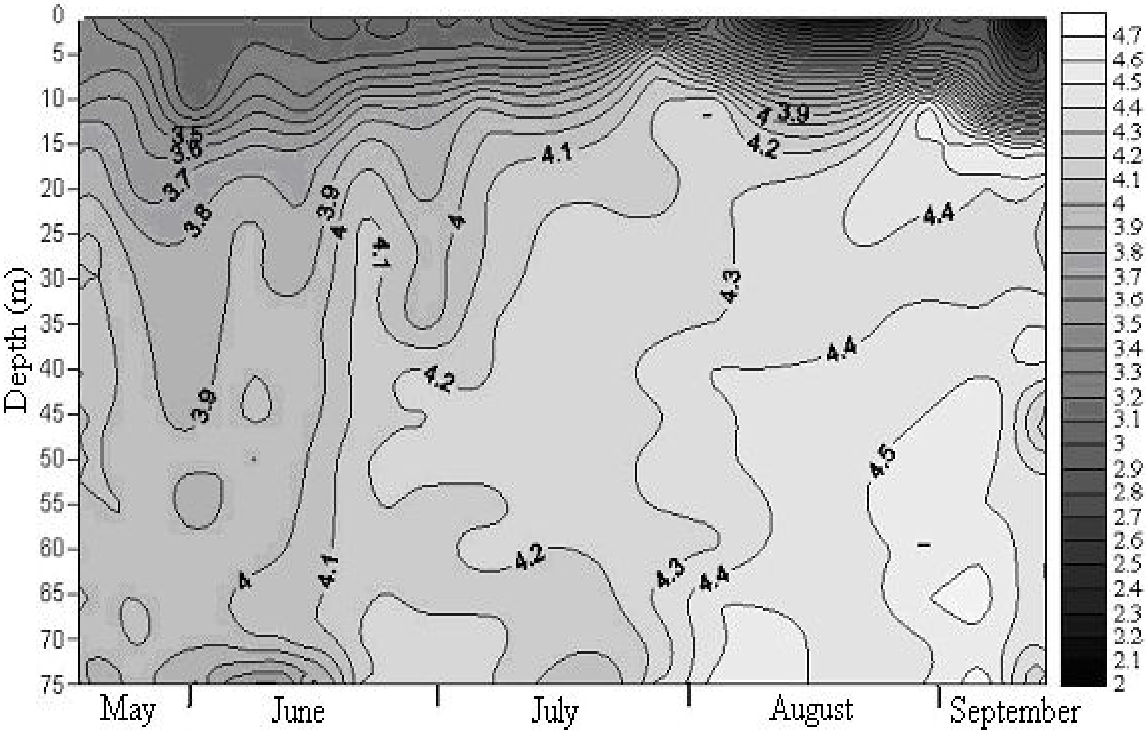

Figure 32. Distribution of dissolved inorganic carbon in water column of Lake Pääjärvi during the summer stratification of the year 2004.

Due to higher alkalinity dissolved inorganic carbon concentrations in Lake Ormajärvi were much higher than in Lake Pääjärvi throughout the stratification period, 6.1-6.5 mg l^{-1} near the surface and 7.2-10.0 mg l^{-1} near the bottom (Fig. 33). Again due to higher alkalinity, the relative variation in dissolved inorganic carbon concentration near the surface was narrower in Lake Ormajärvi than in Lake Pääjärvi. In Lake Ormajärvi the highest values in surface water were found at the late June, whereas near the bottom concentrations increased throughout the whole sampling period (Fig. 33).

After late June there was a tendency of increase in dissolved inorganic carbon concentration in the metalimnion (Figs. 33 and 34) at the same depth zone where oxygen minimum was observed (Fig. 28). Below the thermocline the evolution of dissolved inorganic carbon was rapid, ca. 1 mg l^{-1} month^{-1} at the early summer and ca. 0.8 mg l^{-1} month^{-1} in late stratification period. At each sampling time the highest dissolved inorganic carbon concentrations were found near the bottom of 25 m.

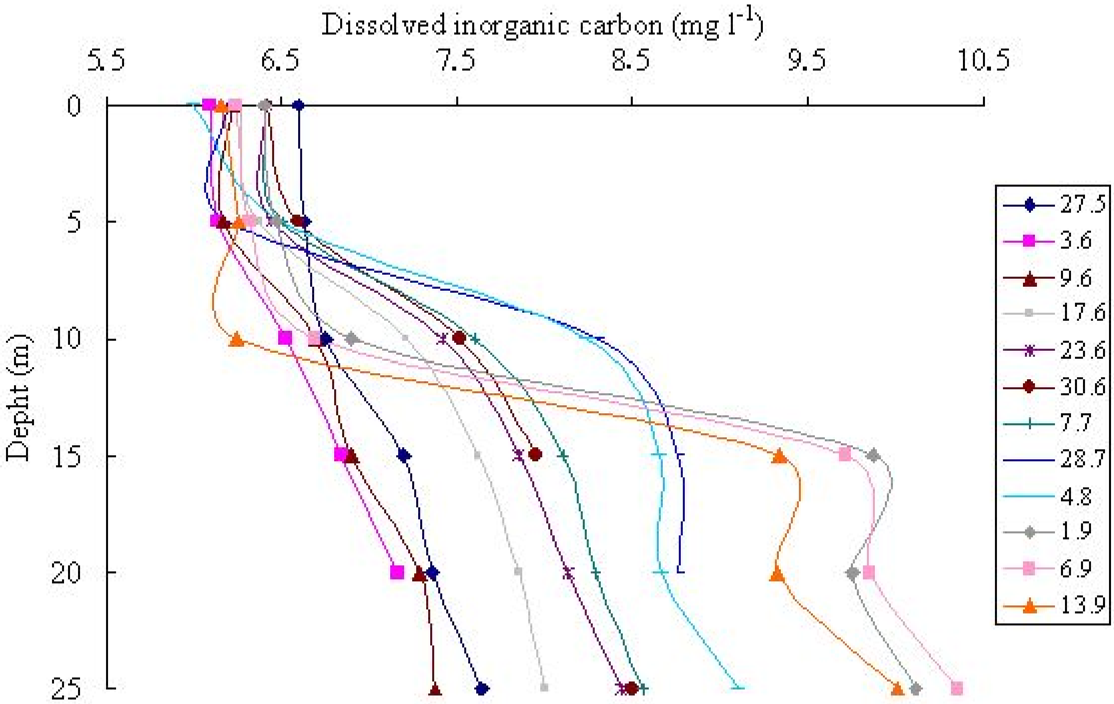

Figure 33. Vertical distributions of dissolved inorganic carbon at different sampling days in water column in Lake Ormajärvi during the summer stratification of the year 2004.

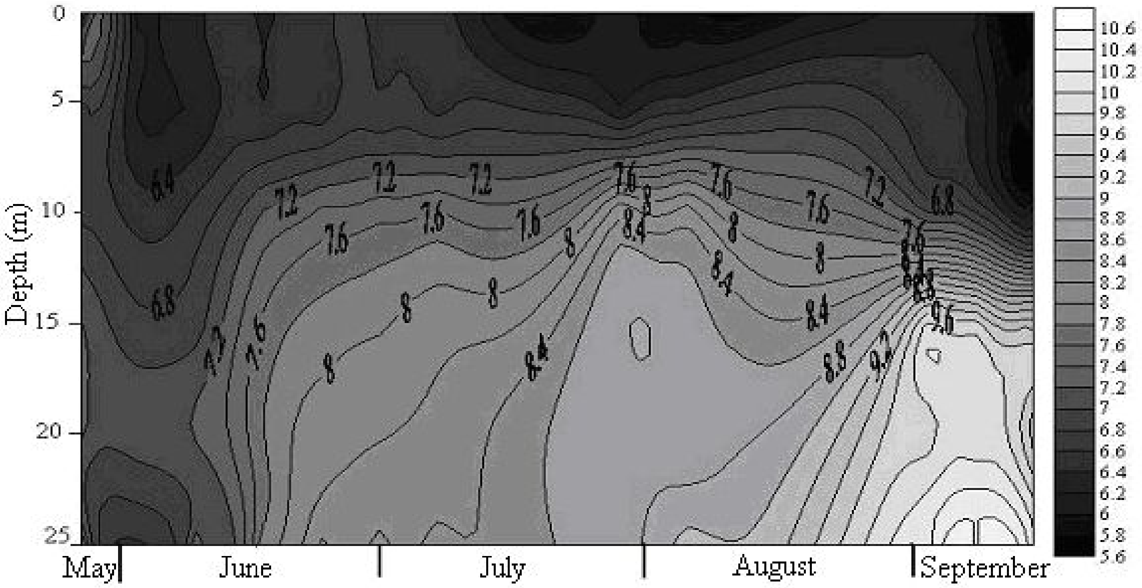

Figure 34. Distribution of dissolved inorganic carbon in water column of Lake Ormajärvi during summer stratification of the year 2004.

4.5 Respiration quotients

In Lake Pääjärvi mean respiration quotient value calculated for water column between 15 to 75 m for the stratification period from 1st of June to 7th of September was 0.89. The highest respiration quotient values were 1.0, whereas the lowest were ca. 0.8. Thus no fluctuation between depths or any sign of increasing respiration quotients with increasing depth could be observed (Table 4). Mean respiration quotients calculated for shorter time periods for hypolimnion from molar dissolved oxygen and dissolved inorganic carbon values were in a range from 0.81 to 2.3. Apart from the highest value, respiration quotients were almost systematically between the range 0.81-1.05. No sign of increasing respiration quotients with increasing duration of stratification was also found.

Respiration quotients calculated for the whole sampling period for hypolimnion (15-25 m) of Lake Ormajärvi gave a mean value of 0.83. The highest value of 0.92 was at the upper limit of hypolimnion, and below that respiration quotients dropped to 0.78 at 25 m (Table 4). Mean respiration quotients calculated for shorter time periods for hypolimnion from absolute molar dissolved oxygen and dissolved inorganic carbon values ranged from 0.58 to 1.53.

Table 4. Respiration quotients in different depths in Lakes Pääjärvi and Ormajärvi during the summer stratification of the year 2004.

Depth (m)	Lake Pääjärvi	Lake Ormajärvi
15	0.80	0.92
20	1.00	0.79
25	0.83	0.78
30	0.80	
35	1.00	
40	1.00	
45	0.83	
50	0.83	
55	0.83	
60	0.83	
65	1.00	
70	0.83	
75	1.00	
Mean	0.89	0.83

4.6 Chlorophyll *a*

In surface water of Lake Pääjärvi chlorophyll *a* concentration ranged from 2.7 to 6.5 μg l^{-1} (Fig. 35). Lowest concentrations were found from May to mid June. From late June chlorophyll *a* concentrations reached slightly higher levels and stayed there till the end of the sampling period. The highest values were found in early August, after which there was a sudden drop in concentration. Then along with increasing mixing depth chlorophyll *a* concentration was rising again.

In Lake Ormajärvi chlorophyll *a* concentrations ranged from ca. 4 to 14 μg l^{-1} (Fig. 35), but the relative change was similar to that of Lake Pääjärvi. Lowest values occurred at early sampling period, whereas concentrations peaked high in the turn of July to August. At early August there was a sudden drop in chlorophyll *a* concentration, but after that it started to rise again, roughly similar pattern that was found in Lake Pääjärvi. In mid September, chlorophyll *a* concentration again reached similarly high level as in July.

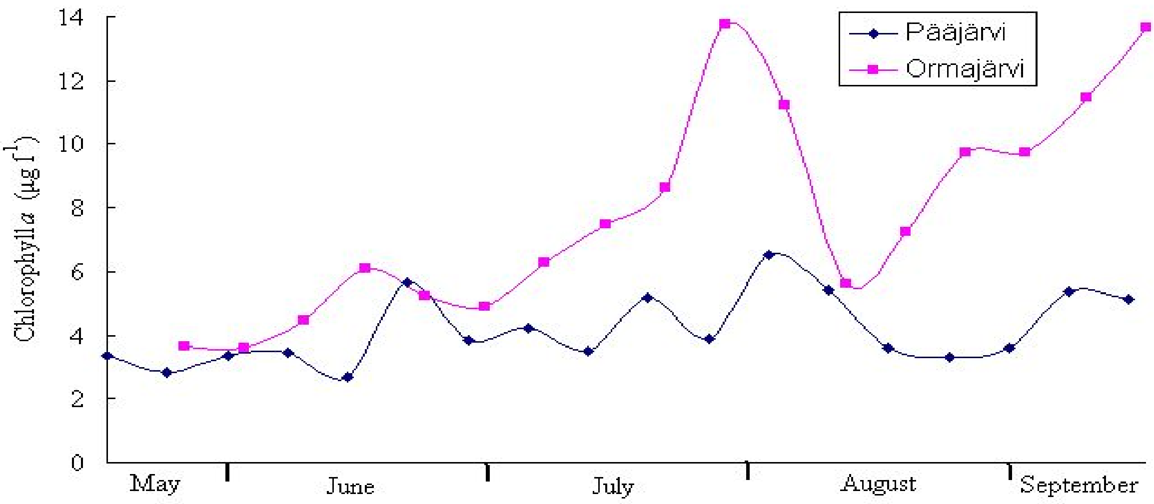

Figure 35. Concentration of chlorophyll *a* in surface water of Lake Pääjärvi and Lake Ormajärvi during stratification of the year 2004.

5. DISCUSSION

5.1 Temperature

Epilimnetic temperatures in Lakes Pääjärvi and Ormajärvi increased until the early August, after which cooling began (Figs. 8 and 10). This was related to the gradual decrease of air temperature especially at night (Fig. 5). However, temperatures in lower metalimnion and in the whole hypolimnion were increasing throughout the whole sampling period in both studied lakes (Figs. 12 and 18), because hypolimnetic temperatures were still very low compared to the upper layers, and therefore gained heat even in early September. High specific heat of water causes temperatures of large water masses to gain and lose heat slowly (Wetzel 2001), and therefore not only hypolimnetic warming during summer, but also the autumnal shift from warming to cooling occurs slowly. This along with the very slow conductivity of heat in water makes the upper hypolimnion to heat up faster than the lower parts.

Highest fluctuations in temperature were found in the upper part of hypolimnion (Figs. 12 and 18). This was probably due to internal seiches, which brought warmer water from the epi- and the metalimnion to the upper hypolimnion. Especially in Lake Pääjärvi big oscillations in temperatures under metalimnion were found during the whole sampling period (Figs. 13 and 14), which indicated that during summer internal seiches could be very regular and important heat transfer mechanism in Lake Pääjärvi. The period of internal seiches of ca. 14 hours was the same as found by Virta (2001) in Lake Pääjärvi. Instead, Hiltunen (1985) found the period of internal waves to be 9.4 hours in Lake Pääjärvi. One and three knot periods calculated with Merian's equation were considerably smaller than the periods of 8 and 2.7 hours found by Hiltunen (1985). This is most likely due to the assumption of a rectangular lake shape of Merian's equation and the difference in determined thickness of the hypolimnion. Lake Pääjärvi basin has a very deep middle part and long shallow bays in its both ends. The length of the main axis of Lake Pääjärvi was the same as found by Hiltunen (1985). Because of long sampling interval in Lake Ormajärvi the dynamics of internal waves remained less clear, but big oscillations in temperature in the hypolimnion are still most likely due to wind induced internal seiches.

The strongest deep water warming in both studied lakes in early summer (Figs. 15, 16 and 19) is reasonable because of low temperature after spring circulation. Although air temperature increased most intensely in early summer the density differences between different depths at low temperatures were much smaller than later in the summer. Still mixing was low and hypolimnetic temperatures especially in Lake Pääjärvi remained low during the stratification period, > 0.5 ˚C colder than during the following summer 2005 (data from this same project). This was probably because of rather exceptional summer of the year 2004, with low air temperatures and high rainfall (http://www.fmi.fi/saa/tilastot_143.html). Hypolimnetic water mass in Lake Ormajärvi was much warmer during the summer than in Lake Pääjärvi (Figs. 12 and 18), because of the relatively smaller hypolimnetic volume compared to epilimnetic volume, and smaller depth than in Lake Pääjärvi. However, when comparing the situation in depth region 0-25 m in both studied lakes, a fairly similar pattern can be seen (Figs. 7 and 9). Still, in late summer, temperature in Lake Ormajärvi in 15-25 m was slightly higher than in Lake Pääjärvi, probably due to smaller volume of that depth region in Lake Ormajärvi. In both lakes hypolimnetic temperature fluctuations and temperature differences between depths between adjacent weeks were higher at the late than at the early stratification. This was related to increased differences in temperature between epi- and hypolimnion, and to internal waves that cause mixing of hypolimnetic water. Clear platforms of minimal temperature increase in hypolimnion of Lake Pääjärvi (Fig. 14) could be related to similar intervals of small change in air temperature (Fig. 5), but in the long run oscillations in air temperatures could not be clearly seen in hypolimnetic temperatures. The warm period during mid August could not be clearly seen in hypolimnetic temperature profiles, which indicated that hypolimnetic currents and mixing during that time were small. Because wind data was not available, further interpretation of this is difficult.

Highest short term changes in weekly temperature increase rates in lower hypolimnion during stratification were found in the deepest parts of the Lakes Pääjärvi and Ormajärvi (Figs. 16 and 19). Currents to the deepest areas could transport heat and cause upwelling of the colder water from the deeper areas (Imboden *et al.* 1983, Wüest *et al.* 1988). The inconsistent situation of slightly higher temperature in 60 m than in upper and lower depths in Lake Pääjärvi throughout the stratification (Fig. 11) was probably due to slight difference in calibration of temperature logger compared to other depths. The systematically higher temperature in 75 m compared to upper depths could be due to same reason or due to salts dissolved into water from sediment. Although no sign of difference in calibration was found in later comparisons of temperature loggers, it should be noted that temperature differences were very small and thus might be due to very small, as such inevitable, differences in calibration. If there are density currents involved in lake hypolimnia, those are caused by temperature differences in early summer and by chemical substances in later summer. Such currents could decrease heat flux to the deepest parts of the lake, because colder water mass flowing to the deeper area can either replace or mix to the water mass lying on the bottom of the lake. However, the cooling by sediment and resulting density currents do not seem to play big role in Lakes Pääjärvi and Ormajärvi in summer. During late stratification slight cooling of the whole water column occurred in Lake Ormajärvi (Fig. 18). This could be related to upwelling of colder water from the deepest part of the lake due to internal seiches. In July and August similar cooling in upper hypolimnion of Lake Pääjärvi could be seen (Fig. 12). Thus the shallowness of Lake Ormajärvi makes it possible that in suitable conditions internal seiches might affect even the deepest layers. Upwelling of cold hypolimnetic water in Lake Pääjärvi have been mentioned by Ilmavirta (1974). The gradual deepening of epilimnion towards late summer is normally caused by increased length of night and slow cooling of epilimnion due to convection currents during night.

5.2 Dissolved oxygen

Metalimnetic oxygen minimum is common in lakes in temperate region. Shapiro (1960) has stated that there are three possible causes of metalimnetic oxygen minimum: i) water masses with lower and higher dissolved oxygen content may change positions; ii) horizontal movement of water that is caused by the shape, size and morphology of the lake; and iii) processes that are consuming oxygen at that particular place. No specified cases in inland waters can be found for the first cause, although it probably can occur in the sea. The second cause is referred to Alsterberg´s (1927) idea of horizontal movements appearing in hypolimnion, that enables the increased oxygen uptake by the sediment, i.e. oxygen consumption in certain depth in sediment moves horizontally nearer the lake centre. This could be related to internal seiches. According to Wetzel (2001) this kind of metalimnetic oxygen minimum is relatively rare and holds only in lakes with gentle slopes. The explanations for the third cause of metalimnetic oxygen minima include the slowing of sinking rate of materials in the colder and denser metalimnion that increases the abundance of organic matter and consequently decomposition (Birge and Juday 1911, Thienemann 1928), methane oxidation (Ohle 1958) and respiration by zooplankton (Shapiro 1960). Relatively higher part of decomposition occurs in the uppermost warmest water layers. Thus the highest part of organic matter sinking to the hypolimnion is decomposed in still rather warm metalimnion. Thus the higher amount of easily decomposable organic matter and temperature together with enough low mixing rate explain why oxygen concentration can develop a minimum in metalimnion. Clear metalimnetic oxygen minimum developed in Lakes Pääjärvi and Ormajärvi at the same time of summer (Figs. 22 and 28), and in both lakes this development was connected to simultaneous increase in chlorophyll *a* concentration in surface water (Fig. 35). The increase is most likely related to strong rainfall in July, which brought nutrients from catchment area to the lake epilimnion. Therefore sedimentation of algae is likely the main reason causing metalimnetic oxygen minimum. On the other hand at that time also the stratification of temperature was strongest thus reducing the mixing and flux of dissolved oxygen from epilimnion. In both studied lakes hypolimnion remained fully oxygenated so that methane oxidation could not have any role in the development of metalimnetic oxygen minimum. The aggregation of copepods in the metalimnion cannot be ruled out because no data was available. However, similar to the results of Shapiro (1960) in Lake Hiidenvesi zooplankton may have contributed to the development of metalimnetic oxygen minimum (Horppila *et al*. 2000).

In Lake Pääjärvi the oxygen consumption in the hypolimnion seemed to develop linearly. This is in line with rather high saturations even near to the bottom. Normally oxygen concentration is affecting respiration rates only in low concentrations of < 1 mg l^{-1} (Cornett and Rigler 1984). In adequate oxygen conditions in Lakes Pääjärvi and Ormajärvi the regression method (Table 2) could be applied for the calculation of oxygen consumption. This approach yields the most accurate results, because it includes many series, effectively equivalents of parallel samples, of determinations each with their own calibrations. Thus the effects of some systematic errors are minimized. However, in this case oxygen consumptions calculated as a difference between initial and final concentrations yielded very similar results.

During stratification oxygen consumption in hypolimnion in Lakes Pääjärvi and Ormajärvi was strongest in the deepest part of the lake, probably due to sediment oxygen consumption (Figs. 26 and 30). Kusnetzow and Karsinkin (1931) stated that reduced dissolved oxygen concentrations could be related to maximum of bacteria. The differences in oxygen consumption between upper and lower part of hypolimnion were rather small, which was possibly caused by higher respiration rate in free water in upper parts due to higher temperatures compensating oxygen import by mixing. The shoulder in 40 m in Lake Pääjärvi, where oxygen consumption seemed to be significantly slower than in upper depths during stratification (Figs. 22 and 25), is probably caused by decrease in temperatures compared to upper depths (Fig. 12). Hypsographic curves (Fig. 1) indicate, that this shoulder is caused by clear decrease in relative area and volume from 40 to 50 m. This shoulder in 40 m seemed to be the lower level to which internal seiches still affect. The differences in oxygen consumption in upper hypolimnion within single depths are most likely caused by internal seiches, that have oscillation periods normally smaller than 24 h. Although internal seiches bring heat to the upper part of hypolimnion, also more oxygenated water is brought to the upper hypolimnion. There were big oscillations in oxygen consumption in Lake Pääjärvi in the deepest part of the lake in 75 m (Fig. 26). The area of 75 m region in Lake Pääjärvi is so small, that the distance between sampling point and bottom was probably different in every sampling occasion. Because the oxygen gradient is steepest near the bottom, big variation in oxygen concentration in the deepest part of the lake is thus likely. The same can also be seen in 25 m in Lake Ormajärvi, where the variation is bigger than in shallower depths (Fig. 30).

Less than 90 % oxygen saturation in hypolimnion in the early phase of the temperature stratification of Lake Pääjärvi suggests that stratification formed so quickly that oxygen concentration did not have time to saturate. This incomplete spring circulation often occurs in small lakes (Hofmann 1975, Hongve 2002). In Lake Ormajärvi of the nearly 100 % oxygen saturation near the bottom after spring circulation indicated complete oxygenation of water, which is possible due to smaller depth of Lake Ormajärvi than Lake Pääjärvi. During early stratification in Lake Ormajärvi both oxygen concentration and temperature gradient in deep hypolimnion indicate (Figs. 18 and 28), that either denser water cooled by the sediment or colder river water flowed down the slope bringing colder, more oxygenated water to the deepest part of the lake. Hypolimnetic oxygen consumption rates in Lake Ormajärvi decreased towards the end of the stratification (Fig. 30), whereas in Lake Pääjärvi rates increased in the lower hypolimnion (Fig. 26). In Lake Ormajärvi low oxygen concentrations at the end of the summer probably slowed down the respiration processes in water and in sediment (Provini 1975, Cowan *et al.* 1996). Later during the stratification period difference between oxygen concentrations in upper and lower parts of hypolimnion of Lakes Pääjärvi and Ormajärvi increased (Figs. 22 and 28). This was probably due to higher oxygen consumption rates in the deepest parts of the lakes. Also internal seiches could have brought more oxygenated water to the upper hypolimnion, down to 40 m in Lake Pääjärvi, and sometimes down to bottom in Lake Ormajärvi. Periods of high oxygen consumption rates can partly be explained by high chlorophyll *a* concentrations. Small differences between high values are also quite sensitive to for example changes in calibration. Oxygen consumption rates in late summer are difficult to interpret, because of long time intervals in sampling (Figs. 25 and 26).

In a temperate dimictic lake Linsey and Lasenby (1985) found hypolimnetic oxygen consumption rate to be ca. 0.3 mg l^{-1} week^{-1}. Similarly Fulthorpe and Paloheimo (1985) found small lakes to have oxygen consumption rates of 0.2-0.4 mg l^{-1} week^{-1} on average. In mesotrophic Lake Pääjärvi oxygen consumption rates were near those found in other dimictic temperate lakes, whereas eutrophic Lake Ormajärvi had significantly higher oxygen consumption rates (Figs. 25 and 30). Of course hypolimnetic oxygen consumption rates are highly related to the lake trophic status (Ahrens and Peters 1991), but it should also be remembered, that lakes with large volume hypolimnion can have higher oxygen consumption rates per unit area than lakes with small volume hypolimnion, whereas reverse is true for oxygen consumption rates per unit volume (Wetzel 2001). Also the high hypolimnetic temperature differences between Lakes Pääjärvi and Ormajärvi are important for the oxygen consumption rates.

Because the diffusivity of heat in water is much faster than diffusivity of dissolved substances, so-called double-diffusion can cause chemical borderlines to occur in lakes, and especially in the ocean (Hoare 1966). This double-diffusion can increase heat flux in hypolimnion by one order of magnitude (Schmid *et al.* 2004). However, in lakes the differences in salinity are normally so small that double-diffusion is insignificant. Different amount of organic matter in different depths due to sedimentation and decomposition might explain why temperature increase rates and oxygen consumption rates did not correlate in the upper hypolimnion, but instead in the lower one during stratification in Lake Pääjärvi (Table 3).

The fluctuations in warming (Figs. 15 and 19) and oxygen consumption rates (Figs. 25 and 30) during the stratification in Lakes Pääjärvi and Ormajärvi were highest in the upper hypolimnion. Mixing and internal seiches induced currents reach the upper hypolimnion more easily than the lower one, carrying heat and oxygen to the upper hypolimnion. Therefore, when temperature increase rate is high, oxygen consumption rates are low and negative correlation between these two occur. The clear oscillation periods seen in temperature increase (Figs. 15, 16 and 19) and oxygen consumption rates (Figs. 25, 26 and 30) are most likely unreal, and due to weekly sampling interval. This could be reasoned by the longer length of oscillations in oxygen consumption rates than in temperature increase rates in both studied lakes. Also the oscillation periods of temperature increase rates are rather constant, whereas clear variation can be seen in oxygen consumption rates. And no such oscillations were seen in temperature time series (Fig. 13). Now these weekly rates are highly sensitive for big daily variation (Fig. 13). Internal seiches could cause high fluctuations and oscillation period to occur in upper hypolimnion of Lake Pääjärvi, but the effect on lower hypolimnion would be very small. In Lake Pääjärvi simultaneous occurring of high epilimnetic oxygen saturation (Fig. 23) and low oxygen consumption rates indicate, that during those peaks in saturation oxygen concentration results have been somewhat too high.

5.3 Dissolved inorganic carbon

The fluctuations in dissolved inorganic carbon concentrations are tightly connected to changes in oxygen concentration, because in aerobic respiration processes oxygen is consumed and carbon dioxide evolved. Therefore low oxygen and high DIC concentrations are normally produced as a result of decomposition. Because of photosynthetic processes in illuminated epilimnion, lowest concentrations of dissolved inorganic carbon were found in the epilimnia of Lakes Pääjärvi and Ormajärvi during the whole sampling period (Figs. 31 and 33). Also higher temperature in epilimnion compared to hypolimnion leads to lower dissolved inorganic carbon concentration, because less carbon dioxide is dissolved in warmer water. Highest epilimnetic concentrations were found at the late June after period of strong winds that caused epilimnion to mix (Figs. 32 and 34). This is supported by the clear increase in chlorophyll *a* concentration at that time (Fig. 35). Concentrations in hypolimnion, however, were significantly higher throughout the stratification period, because of respiration in the sediment and in open water of the hypolimnion (Cornett and Rigler 1987). Although due to higher alkalinity and throphic status dissolved inorganic carbon concentration and evolution rate were higher in Lake Ormajärvi than in Lake

Pääjärvi (Figs. 31 and 33), similar pattern can be seen in both lakes in the depth region 0-25 m. During late summer weak metalimnetic dissolved inorganic carbon maximums could be seen in both studied lakes, which were clearly connected to metalimnetic oxygen minimum described earlier. Dissolved inorganic carbon maximum in metalimnion was not as clearly seen as oxygen minimum, because of very high concentrations in the hypolimnion.

In both studied lakes the changes in conditions during stratification were more clearly seen from the results of dissolved oxygen than from those of dissolved inorganic carbon. This is mainly due to higher precision on dissolved oxygen determinations. Especially in Lake Ormajärvi high portion of HCO_3^- in dissolved inorganic carbon tends to mask small changes in dissolved inorganic carbon concentration. However, altogether the results of oxygen consumption and dissolved inorganic carbon accumulation showed fairly similar trends.

5.4 Hypolimnetic density currents

Bottom currents driven by the temperature gradient between water and sediment probably occurred only during the early part of stratification, when the temperature gradient was highest. This was indicated by clear drop in water temperature in late May in Lake Ormajärvi. The density currents may partly explain why the differences between depths in temperature in hypolimnion were higher at the early period of stratification (during May) than later in the summer (Fig. 12), since these currents could bring colder water to the lower part of hypolimnion. It should be noted that when temperature is lower in early stratification, density differences are smaller than in higher temperatures, and therefore the intensity to mix is greater in early summer, i.e. stratification is weaker in early summer when wind induced current and mixing patterns reach hypolimnion more easily. However, strong wind periods occurred only at the early June (personal observation), which cannot be easily seen in temperature or oxygen profiles. The differences in oxygen concentration at the early period of stratification were minimal between depths, which indicates that there was still some mixing occurring. Bryson and Suomi (1951) shoved, that density currents could be major forces transporting dissolved oxygen into lake deeps. Diffusive processes occur in hypolimnion throughout the stratification period (Virta 2001), but hypolimnetic mixing and water exchange at that time are probably mostly caused by internal seiches and bottom currents (Imboden *et al.* 1983). According to temperature data internal waves can be found in Lake Pääjärvi already at the early part of stratification period (Fig. 13). Imboden *et al.* (1983) showed that in strongly stratified lake internal waves could have oscillations with high frequencies and high amplitudes with a persistence of clearly over a week. The east-west orientation of Lake Pääjärvi, parallel with prevailing winds, makes it sensitive to these oscillations, and the duration of the oscillation periods fit well within the range of 6-16 hours observed for the lakes of similar size as Lake Pääjärvi (Wetzel 2001). Although damping of internal waves occurs, these wave patterns are normally destroyed by new wind. Hiltunen (1985) found, that depending on the shape of the lake and slopes of the litoral zone one or more differently oriented internal seiches can occur. He found, for example, that in Lake Pääjärvi directions of the two main seiches differ ca. 40°. As results indicate, internal seiches have strong influence in hypolimnetic mixing during summer stratification in lakes. It should be noted, that there are also other waves, e.g. Kelvin waves (Horne and Goldman 1994, Wetzel 2001), which can have the same period as internal seiches or standing waves. The effect of Kelvin waves to the mixing of litoral zones may be significant (Horne and Goldman 1994).

According to Imboden *et al.* (1983) bottom currents during summer are mostly related to wind. They also found, that these currents cause hypolimnetic water renewal of about 10-15 % per month during summer period. Wüest *et al.* (1988) showed that density currents exist during spring and early summer in Lake Lucerne and that those had significant impact on hypolimnetic temperatures. Although river inputs had significant effect on bottom currents, also internal sources causing chemical and temperature differences were the origin of these density currents.

5.5 Respiration quotients

The mean respiration quotients (Table 4) for both studied lakes were quite near the general theoretical value of about 0.85, which is estimated for oxidation of proteins for inland waters (Ohle 1952). The oxidation of carbohydrates generally have values near one. Respiration quotients in Lakes Pääjärvi and Ormajärvi match quite well the mean value of 0.9 estimated by Granéli (1979) for four Swedish lakes. Anaerobic metabolism during stratification period can increase respiration quotients significantly higher than one, when CO_2 is evolved without the consumption of O_2 (Murray and Rich 1995). Respiration quotients of > 1 were found in both studied lakes. However, this should have also been seen in increased respiration quotient values during stratification (Rich 1975), which did not occur in the studied lakes. This is probably due to high variation due to small differences in concentrations of dissolved oxygen and carbon dioxide, which also made the calculations of respiration quotient values for shorter time periods unreasonable. In short time intervals precision of results and calibration cause higher variation into calculated differences. Still the results in Lake Ormajärvi support the high portion of sediment oxygen consumption. Especially the hypolimnion in Lake Pääjärvi was well aerated during the whole sampling period, which may be one explanation for no increase in RQ values. In theory respiration quotients can not be > 1 in aerobic water, so the high values in both studied lakes are most likely due to variation caused by errors in determination and calibration.

5.6 Future work and improvements

It would have been ideal situation, if sampling could have been started already when the lakes were still circulating. The lack of sediment temperatures from different depths in hypolimnion throughout the sampling period was a major gap in order to detect the heat exchange between sediment and water. Also measurements of temperature, dissolved oxygen and dissolved inorganic carbon from different horizontal planes with shorter time intervals could have given further information about the currents occurring near the sediment-water interface. Now data were collected from single points from only the deepest parts of the lakes, which allowed only the deepest sampling depth to be near the sediment. The emerging new equipments such as fluorescence quenching based oxygen determination will provide necessary tools which can be used in the field in a way similar to present CTDs enough rapidly so that large scale areal approaches become feasible. The rest of the sampling was made from the free water away from sediment surfaces. There were also no measurements of water from the rivulets, which may contribute to the hypolimnetic conditions and water quality (Lambert *et al.* 1976). Additional data from wind patterns and other chemical parameters would also be relevant when trying to identify the sources of hypolimnetic currents.

The results suggest, that in fine details hypolimnetic temperature and oxygen concentration are very dynamic variables. Hypolimnion is not strictly isolated body of water but affected by currents with various origins, element exchange between water and sediment and organic matter fed from the epilimnion. All these contribute to the development of the concentrations of respiratory gases and consequently may influence, for example, the leakage of nutrients from the sediment.

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