Some Physical and Environmental Aspects of Shallow Ice Covered Lakes

Emphasis on Lake Vendyurskoe, Karelia, Russia.

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Some Physical and Environmental Aspects of Shallow Ice Covered Lakes

Emphasis on Lake Vendyurskoe, Karelia, Russia

Osama Ali Maher

DOCTORAL DISSERTATION

by due permission of the Faculty of Engineering, Lund University, Sweden.
at the Department of Building and Environmental Technology, John Ericssons väg 1,
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Abstract

The ice cover presence on the surface of a lake insulates the water body from the atmosphere. This prevents or reduces the influence of processes which depend on the exchange between the atmosphere and the water surface. This implies significant reduction or elimination of some processes taking place at the open water surface; for instance, a substantial reduction in solar energy penetrating to the water body. This reduction of heat input from the atmosphere is partly compensated for by heat flux from sediment. Wind induced currents are replaced by oscillating currents due to wind action on the ice cover. Sediment heat flux generates slow density currents along sloping bottoms. This study is almost exclusively devoted to Lake Vendyurskoe, a small lake in the Russian Republic of Karelia. On Lake Vendyurskoe, ice is usually formed in November-December and it remains for a duration of six to seven months. The maximum ice thickness is 60-80 cm. The ice growth can be well described using a degree day equation.

The water temperature was measured continuously in several vertical profiles in the lake. Heat fluxes at the water-ice interface and at the sediment-water interface were determined by measuring temperature gradients. Due to gain of heat from the sediments, the heat content of the ice covered lake increased throughout the ice covered period. At the time of freeze-over, the water temperature is less than 0.5 oC all the way to the bottom. In April, the temperature profile is almost linear from 0 oC at the underside of the ice to 4 oC or more at depth below 8 m. The heat flux conducted from water to ice soon after ice formation is about 1 W·m-2 , but it increases in the course of the winter and can reach 5 W/m2 in early spring. The sediment heat flux to water increases throughout the winter and is highest in early winter and at shallow bottoms, where the sediment is warmest, and the water is coldest. Typical values are, directly after the ice formation, 2-6 W·m-2 and by early spring 1-2 W·m-2. Oscillation of the ice cover due to wind action produces small horizontal currents and mixing. These currents were measured during several campaigns with an acoustic meter. They had an average magnitude of about 2 mm·sec-1 and a maximum value of 7 mm.sec-1.

In early spring and in absence of snow on the ice, considerable amount of solar radiation penetrates the ice cover and introduces hydrodynamic instability and convective mixing. A vertically homogeneous temperature layer develops, which grows downwards.

The depletion of oxygen and development of dissolved oxygen profiles during winter were investigated. The dissolved oxygen content at the time of freeze over was close to saturation over the entire water body. The dissolved oxygen reduces throughout the winter, but much more at deep water than at shallow water. Near the sediments, the concentration drops to low values. It is found that diffusion of oxygen into the sediments is the dominating consumption process. When there is convective mixing under the ice in early spring, the dissolved oxygen is redistributed over the homothermal layer. This can, because of the water movements, be associated with increase of the diffusion into the sediments which leads to a decrease of dissolved oxygen also at shallow water.

Key words convective mixing, dissolved oxygen, heat exchange ice–water, ice cover, oscillatory currents, sediment heat fluxes, water temperature

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بِالْأَمْسِ كُنْتُ ذَكِيًّا وَ أَرَدْتُ تَغْيِيرَ أَلِعَالَمِ
أَلِيَوْمِ صُرْتُ حَكِيمَ وَ أُرِيدُ تَغَيُّرَ نَفْسِي
مَوَّلَانَا

“*Igår var jag smart och ville förändra världen*

Idag, jag är klok och vill förändra mig själv”

“Yesterday I was smart and wanted to change the world

Now, I am wise and want to change myself”

-Rumi

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Colleagues at the Northern Basins Research Institute in Karelia, Russia, I deeply express my gratitude to colleagues at the Northern Water Problems Institute at the Russian Karelia for their support during field campaigns; Dr. Arkady Terzhevic and Dr. Sergei Golosov for all their valuable cooperation on many of the field campaigns and joint publications.

To my family: Ali Maher, you left too soon but your soul were always there, Magda, and Ali because of you I would have never looked for what I aimed for. Thanks to all members of my family for support and for being too patient with me.

Popular science summary

Northern lakes are ice covered for large parts of the year. After ice formation, the lake becomes almost isolated from the atmosphere and hence, there is no direct loss of heat to the atmosphere, no exchange of oxygen between air and the water body and no wind generated currents. Due to wind action on the ice cover, some oscillating currents are generated; small in magnitude but they contribute to the horizontal mixing of the water body. The lake sediments are heated during summer. This heat is released to the water, when the lake is ice covered. Because of density anomalies the bottom water is warmer than the 0 degree water at the underside of the ice. The heat flux from sediments to water is the main contributor to the warming of lake water throughout the winter. When the water becomes warmer it becomes denser and moves along sloping bottoms towards deeper parts of the lake causing slow large scale convection.

In winter, solar radiation is low and there is snow on the ice cover: No solar radiation reaches the water beneath the ice. The photosynthesis process diminishes. While in spring, when the ice cover is snow free abundance of sun rays can penetrate the ice cover. Energy from the sun at this late winter period, in April, heats the top layer of the water column and thus the water becomes denser and that leads to intense mixing convection, which happens on a short scale and results in a mixed homogenous layer, whicj moves a few meters downwards.

While direct wind induced currents dominate in ice free lakes, in ice covered lakes wind action on the ice cover generates oscillatory movements of seiche type. Together with the two types of convective mixing mentioned above, these are the mixing processes in ice covered lakes. Currents generated by river inflow are seldom of importance.

The ice cover almost prevents oxygen supply from the atmosphere, and limits the photosynthesis leading to continuous drop of oxygen level mainly due to consumption of DO at the bottom sediment by organic materials. At the bottom, DO can be completely absent from the water, and by late winter zero oxygen layer can develop above the sediments. By early spring, when sunrays penetrate the almost ice-free cover, difference in water temperature along the water column, leads to difference in water density and the creation of a mixing.

The present study focused on Lake Vendyurskoe in Russian Karelia. The main focus was on the thermal regime of the ice covered lake and on the development of the oxygen content with depth. An analytical model for the development of DO with depth and time was suggested. Heat fluxes at the interface sediment-water and ice-water was determined as function of time after ice formation. Special focus was on the convective mixing in spring when solar radiation penetrated the ice. During this period the dissolved oxygen in water is redistributed and the uptake of oxygen in the water body by sediments increases.

Populärvetenskaplig sammanfattning

Sjöar I norra jord klottet är istäckta stora delar av året. Efter isbildning blir sjön nästan isolerad från atmosfären och följaktligen finns det ingen direkt värmeförlust till atmosfären, inget utbyte av syre mellan luft och vatten och inga vindströmmar. På grund av vindkraft på ishöljet genereras vissa svängande strömmar; små i storlek men de bidrar till den horisontella blandningen av Sjövatten. Sjösedimenten värms upp under sommaren. Denna värme släpps ut i vattnet när sjön är isbelagd. På grund av täthetsanomalier är bottenvattnet varmare än null graders vid isens undersida. Värmeflödet från sediment till vatten är den främsta bidragaren till uppvärmningen av sjövatten under vintern. När vattnet blir varmare blir det tätare och rör sig längs sluttande botten mot djupare delar av sjön och orsakar långsam konvektion i stor skala.

På vintern är solstrålningen låg och med snö ovan på ishöljet: Ingen solstrålning når vattnet under isen och fotosyntesprocessen minskar. Under våren, när ishöljet är snöfritt, överflöd av solstrålar kan tränga igenom ishöljet. Energi från solen under den sena vinterperioden, i april, värmer upp det översta skiktet i vattenspelaren och därmed blir vattnet tätare och det leder till intensiv blandningskonvektion, vilket sker på kort skala och resulterar i ett blandat homogent skikt som rör sig några meter nedåt.

Medan direkt vindinducerade strömmar dominerar i isfria sjöar, i isbelagda sjöar genererar vindkraft på ishöljet svängande rörelser av seich-typ. Tillsammans med de två typerna av konvektiv blandning som nämns ovan är dessa blandningsprocesser i isbelagda sjöar. Strömmar som genereras av flodinflödet är sällan av betydelse.

Ishöljet förhindrar nästan syretillförseln från atmosfären och begränsar fotosyntesen vilket leder till kontinuerligt sjunkande syrenivå främst på grund av konsumtion av syre i botten sediment av organiska material. I botten kan syre vara helt frånvarande från vattnet, och i slutet av vintern kan noll syrelager utvecklas ovanför sedimenten. I början av våren, när solstrålar tränger igenom det nästan isfria skyddet, leder skillnaden i vattentemperatur längs vattenspelaren till skillnad i vattentäthet och skapandet av en blandning.

Den nuvarande studien fokuserade på sjön Vendyurskoe i ryska Karelen. Huvudfokuset var den termiska regimen i den isbelagda sjön och på utvecklingen av syreinnehållet med djupet. En analytisk modell för utveckling av syre med djup och tid föreslogs. Värmeflöden vid gränsytesedimentvattnet och isvatten bestämdes som funktion av tiden efter isbildning. Särskilt fokus var på konvektiv blandning på våren när solstrålning penetrerade isen. Under denna period återfördelas vattenupplöst syreinnehåll och syreförbrukningen i sedimentet ökar

Abstract

The ice cover presence on the surface of a lake insulates the water body from the atmosphere. This prevents or reduces the influence of processes which depend on the exchange between the atmosphere and the water surface. This implies significant reduction or elimination of some processes taking place at the open water surface; for instance, a substantial reduction in solar energy penetrating to the water body. This reduction of heat input from the atmosphere is partly compensated for by heat flux from sediment. Wind induced currents are replaced by oscillating currents due to wind action on the ice cover. Sediment heat flux generates slow density currents along sloping bottoms. This study is almost exclusively devoted to Lake Vendyurskoe, a small lake in the Russian Republic of Karelia. On Lake Vendyurskoe, ice is usually formed in November-December and it remains for a duration of six to seven months. The maximum ice thickness is 60-80 cm. The ice growth can be well described using a degree day equation.

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Keywords: convective mixing, dissolved oxygen, heat exchange ice–water, ice cover, oscillatory currents, sediment heat fluxes, water temperature

Papers

Appended papers

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals. The papers are appended at the end of the thesis.

I. Maher, O. A., & Malm J., (2003): Seasonal variability of Thermal regime in a shallow ice covered lake. Nord. Hydrol., *34*, 1/2,. 107–124.

II. Maher, O. A., Uvo, C. B., & Bengtsson, L. (2005). Comparison between two extreme NAO winters and consequences on the Thermal regime of Lake Vendyurskoe, Karelia. Journal of Hydrometeorology, 6(5), 775-783.

III. Maher, O. A. (2002, December). Effect of Spring Warming on Dissolved Oxygen Content in a Shallow Ice Covered Lake. In Ice in the Environment: Proceedings of the 16th IAHR International Symposium on Ice, Dunedin, New Zealand (Vol. 16, pp. 41-47).

IV. Golosov, S., Maher, O. A., Schipunova, E., Terzhevik, A., Zdorovennova, G., & Kirillin, G. (2007). Physical background of the development of oxygen depletion in ice-covered lakes. Oecologia, 151(2), 331-340.

V. Bengtsson, L., & Ali-Maher, O. (2020). The dependence of the consumption of dissolved oxygen on lake morphology in ice covered lakes. Hydrology Research.

Author’s contribution to appended papers

Article I:

- The author planned work related to data collection and analysis as well as summarizing all work done on Lake Vendyurskoe prior to the examined years of investigation
- Preparing the outline of the article including graphs and tables
- Being the first author of the article, all communication with the publisher was carried out by Maher as well as the revision of the manuscript according to reviewer’s requirement.

Article II

- The author planned the study with co-authrs, made all calculations, measureements and the analysis with the advices of the co-authors.
- Prepared and finalized the text of the article with the assistance of the co-authors.

Article III

- The author planned the study, made all measureements, calculations, analysis.and wrote the text.

Article IV

- The author assisted the forst author by conducting and providing data from field campagins and the data analysis.
- The author assisted as well in the discussion of the final results and validation of proposed model.

Article V

- The author made the measurements and provided the data on Lake Vendyurskoe and the calculation and assisted the first author with physical analysis.

Abbreviations

BOD	Biological Oxygen Demand
DO	Dissolved Oxygen
CM	Convective Mixing
ICL	Ice Covered Lake
LV	Lake Vendyurskoe
ML	Mixed Layer
NAOI	Northern Atlantic Oscillation Index
NH	Northern Hemisphere
NWPR	Northern Water Problems Institute
SOD	Sediment Oxygen Demand
SYKE	Finnish Environment Institute
TVRL	Teknisk Vatten Resurslara
UML	Upper Mixed Layer

Contents

Introduction

Lake surface in most lakes in the Northern Hemisphere freezes for periods varying from a couple of weeks to almost the entire winter period. Relatively, little research has been devoted to study these lakes during the ice-covered period. Lake physical and environmental conditions are very distinct whether the lake surface is free to the atmosphere or is ice covered. Thus, an improved knowledge of physical processes in Ice Covered Lakes (ICLs) is needed for a better understanding of environmental conditions of these types of lakes. After the formation of the ice cover, water is isolated from the atmosphere, so the thermal regime is dominated by heat flux from sediment to water. The same effect can be observed for Dissolved Oxygen (DO), where lack of aeration and DO diffusion in sediments lead to decrease in the DO content through the winter. Wind action on the ice cover results in oscillatory movements and weak horizontal mixing of lake water.

Ice formation on lakes usually takes place during early winter following several days of below zero air temperature and calm wind conditions. The ice cover, in many cases, forms and disappears several times before a stable winter ice cover is established (Fang et al 1996 and **Paper I**). Climatic conditions in the Northern Hemisphere are sensitive to the Northern Atlantic Oscillation (NAO). An analysis of the direct effect of the index on the climatic conditions in the Northern Hemisphere and hence an indirect effect on lakes characteristics is investigated (**Paper II**).

Directly after an ice cover has formed, (**Papers I and II**) the warming of lake water is taking place throughout the winter due to the release of heat stored in the bottom sediment during the summer. At deep parts of the lake, the temperature is reaches 4 °or even higher.

In flowing rivers, can induce currents in water body under the ice cover, but these are usually negligible in these types of lakes. However, in Lake Vendyurskoe with almost no inflow, oscillating currents as well as temperature and density induced currents are the type of currents which produce horizontal mixing (**Papers I and II**). Vertical mixing takes place during early spring as a result of the thermal instability caused by solar radiation penetrating the ice cover (**Papers III and IV**).

The ice cover prevents the exchange of DO between the atmosphere and lake water. This is usually associated with decrease in the production of the DO by photosynthesis due to less light penetrating through the ice and snow cover.

Decrease in DO supply through atmosphere and photosynthesis is usually coupled by an increase of Sediment/Biological and Oxygen Demand (S/BOD) due to the increase in biological respiration and chemical oxidation above the sediment, this process is highly depending on lake morphology as stated in **Paper V**. Early spring convection results in mixing of the top meters of water and the redistribution of DO (**Paper IV and V**).

The present document is devoted to describing and drawing conclusions regarding some physical, chemical and environmental characteristics of small shallow lakes, of the order 10 km^2 and 10 m depth. For this purpose, several field measurements campaigns are presented for Lake Vendyurskoe in Russian Karelia and to some extent Lake Velen in Sweden, which are representative to this type of lakes.

Lake Vendyurskoe is the scope of this study due to availability of physical and environmental data collected during winter periods since as early as 1980's. A long-term cooperation was established in early 1990's and continued for more than a decade between the Department of Water Resources Engineering, Lund University, Sweden (TVRL), and the Northern Water Problems Institute, Petrozavodsk, Russia. This cooperation resulted in many joint field measurements campaigns which are included in all publications of the author.

In addition to direct field investigations and a review of some published literature on similar lakes, this document presents some empirical models dealing with several processes and dynamics of these lakes, specifically those related to Dissolved Oxygen (DO) and thermal regime.

This report is structured in the following way; first, a background on some of the characteristics of shallow lakes during ice cover periods, including climatic conditions and ice cover development, water temperatures, heat fluxes, currents and dissolved oxygen. Later, the study site is presented with previous studies on the same lake following results of measurements campaigns, and finally conclusions and recommendations.

Objectives of this study

This dissertation is aiming to give a comprehensive understanding of physical process in lakes in Northern Hemisphere during the ice cover period and during the spring and ice cover break up. The focus here will be to show and quantify physical processes in winter lakes with emphasis on heat fluxes during different phases of the ice covered period and the consequences on heat balance, circulation and dissolved oxygen and how it relates to large scale meteorological systems. A special attention is given to the period directly before the break-up of the ice cover when a convective mixing is taking place and leads to dramatic changes in the water body starting by breaking the winter temperature stratification and changing the oxygen content of the water.

The specific objectives of this dissertation are:

- To understand climatic drives behind the evolvement and decay of the ice cover on lakes and to explore the climatic factors affecting these two processes, specifically the Northern Atlantic Oscillation Index (NAOI).
- To quantify the processes related to thermal regime under the ice cover throughout the whole winter.
- To show the effect of solar radiation on the water temperature and circulation during the period directly before the ice cover break up.
- To examine the factors affecting the dissolved oxygen content of lake water during the ice cover period including the role of lake morphology.

Environments of ice covered lakes

Ice and snow cover

Ice and snow cover properties on temporarily frozen lakes and the extent of the ice cover period are important for the eco system, biota and water quality. The ice cover parameters such as thickness, composition, freeze and break-up dates, and ice cover duration length are good indicators of regional climate change in high-latitude areas. In a recent study by Korhonen (2019) on the long-term changes in hydrological regimes in Finland, a systematic approach used by the Finnish Environment Institute (SYKE) was presented to describe the ice freeze and break-up processes. Ice formation starts from the shores, then covering bays and then the full lake surface. In spring, first the snow on the ice melts. Then the ice melt from the surface, but there is also internal melting. The break-up of ice cover usually starts by thawing of the shore ice until the shores are ice free, then ice sheets start to move and finally the lake surface is ice free. Even though this approach represents a logical, well defined and structured freezing and breakup of the cover in lakes, this sequence can be problematic when trying to have an "official" reference dates for the start and end of the ice covered period. In many cases and depending on many factors, such as lake morphology and meteorological conditions, these stages can be mixed or do not follow the mentioned sequence. For instance, severe cold conditions can lead to a mix of all stages.

The ice cover starts to appear on a lake after days with below zero degrees of air temperature and usually starts from the shore and advances towards the lake center. This progression towards the center depends on the heat balance along the vertical water column. The lake ice cover can be composed of four different layers; firstly, black ice which is a result of heat loss from the water to the atmosphere. Snow over the ice cover represents an obvious layer of the "cover". When the accumulated snow weight becomes heavier than the buoyancy force, water starts to seep from the water column to the ice cover surface and starts to freeze within the snow forming a layer of white ice to become the third possible layer of the ice cover. When this white ice melts or if the seeped water did not freeze, slush becomes the fourth possible layer of the ice cover (Leppäranta 1983, 2010, 2014).

Climate and lake ice cover

Ice formation and breakup depend on the energy balance at the water atmosphere interface and hence time of freeze over may vary rather much from year to year. Daily average air temperature, wind speed, and initial average water temperature are the main factors determining the date of ice formation (Gu & Stefan, 1990). In a study by Korhonen (2006) on the freeze-up and break-up records of ninety Finnish lakes, and ice thickness of about thirty lakes, it showed that there is a significant change towards earlier ice break-up in Finland from the late 19th century to the present time. The analysis showed that there is a significant trend towards later freeze-up and thus shorter ice cover duration. The study revealed that ice thickness has increased over the past 40 years. The trend of ice thickness increase was observed in almost half of the investigated lakes. However, a significant decrease in the maximum ice thickness was found in four lakes in southern Finland. The increased ice thickness is most likely due to heavy snow on the ice and production of snow ice.

In addition to the direct linkage to the local weather conditions, the ice covered period length and the characteristics of the ice cover may be linked to global climatic indices. The Northern Atlantic Oscillation (NAO), which is a meridional alternation in atmospheric mass between the subtropical atmospheric high-pressure over the Azores and the atmospheric subpolar low-pressure over Iceland was reported by several studies to have an effect on the climate in the Northern Hemisphere (Van Loon & Rogers, 1978; Wallace & Gutzler, 1981; Hurrell, 1995; Maher & Malm, 2003). NAO is commonly represented by an index (NAOI) based on the difference of the sea level air pressure measured at a meteorological station close to the center of the Azores High (Lisbon, Gibraltar or Azores) and that measured at a station in Iceland (Hurrell, 1995). Positive winter values of NAOI correspond to strong meridional pressure gradient, on its turn associated to strong westerly winds that transport warm, moist and maritime air across Northern Europe, giving rise to mild and wet winters (Straile et al., 2003). In contrast, low NAOI values correspond to weak westerlies and cold dry winters in Northern Europe.

Ice cover growth and decay

The growth of ice cover proceeds as a balance between heat losses through the ice and ice production at the underside of the ice, black ice. Lake ice evolution, if not directly measured can be dealt with rather straight forward using heat conduction analysis or by using regression or empirical models, or energy balance models computations. The static ice growth is often estimated from Stefan's equation:

$$h_s = C\sqrt{S} \tag{1}$$

$$S = \sum_{Daily}(-T_{air}) \tag{2}$$

where C is a degree day coefficient that depends on the status of the ice cover. If the ice cover is composed of black ice only, the coefficient is 3.5 cm/ (°C day)1/2; when snow is present on the ice, the coefficient is about 2.0 cm/ (°C day)1/2 (Bengtsson, 1986). S is the accumulated value of the daily negative air temperature.

Ice cover thickness was calculated using this approach and compared with measurements (using observed days of ice formation). Good agreement was obtained using C = 2 cm/ (°C day)1/2.

The ice thickness decay and disappearance of the ice cover process is more complicated. The melting is from the top of the ice/snow surface, but there is also internal melting from solar radiation and some minor melt from heat flux from the water to the ice. The decay of an ice cover is a process that can take weeks. Also, for the melting of lake ice, a degree-day method is the simplest approach to be used, for example Bilello, (1980).

$$h_{max} = C\ S \qquad (3)$$

The degree-day coefficient is the accumulated positive degree days and is larger in value than the coefficient during ice formation, about 0.5 cm/(°C day)^1. The first break-up can happen fast when there are sunshine and strong winds.

Thermal regime

The dynamic processes differ significantly if the lake surface is free or covered with ice. During summer, heat is conducted from the water to the sediments. Later, the heat content in dimictic lakes decreases throughout autumn being homothermal at 4°C and continuing until the surface water reaches 0°C for ice cover to form. The temperature at the bottom is 4°C or less (Hutchinson, 1957; Bengtsson & Svensson, 1996; Ellis et al., 1991).

The heat is released back to the water during winter, when the water is colder than the sediments. The temperature increases continuously over time in the lake during the ice-covered period as a result of this heat flux from bottom sediments (dominant in early and mid-winter).

General water temperature structure under ice during the ice cover period is largely understood and documented by several studies starting from work of Birge et al., (1927) and later on by numerus studies (Rogers, 1992; Rogers et al., 1995; Bengtsson & Svensson, 1996; Bengtsson et al., 1996; Malm et al., 1998, Bengtsson, 2011), including those of Lake Vendyurskoe where all field measurements in this thesis were taken.

Dissolved Oxygen

Dissolved Oxygen is an essential element of the ecology of lakes and affects the distribution and diversity of organisms (Tonn & Magnuson, 1982; Rahel, 1984; Nürnberg, 1995). The DO content in lake water is controlled by two opposite sets of processes: those consuming oxygen and others replenishing it. Both processes are greatly influenced by the low temperature of the water body during the ice-covered period and are limited by the existence of ice cover, Greenbank (1945). The oxygen is supplied to the water body mainly by two sources: diffusion through the atmosphere-water interface which then is distributed to the rest of the water body through mixing processes, and by photosynthesis of algae. If the water body is ice-covered, the ice cover prohibits the diffusion of oxygen from the atmosphere to the water body and almost completely hinders solar radiation to penetrate the ice/snow cover into the water and reduces or diminishes the photosynthesis process. The lake content of the DO in the water is decreased through respiration of water organisms, bacterial oxidation of organic matters and chemical oxidation of inorganic substances and by consumption by lake sediment (Maher et al., 2004; Golosov et al., 2007). The importance of the process of exchange of dissolved organic molecules, organic ions, and gases between the sediments and the water column for biological and geochemical processes in lakes has been reported in many studies e.g. (Jorgensen & Revsbech, 1985). Many of these studies have been directed towards methods of sediment oxygen consumption and challenges associated with the measuring techniques of the rate of this uptake (see for instance Hargrave, 1972; Pamatmat, 1971).

The oxygen transfer rate through the sediment surface takes part as diffusion which depends, apart from the oxygen demand, on water movements above the bottom and on available oxygen in the bottom water. Faster water velocities at the sediment-water interface increase the mass transfer rate by decreasing the thickness of the diffusive/viscous boundary layer (Jorgensen & Revsbech, 1985). The diffusion rate is virtually molecular within the sediment, (Lorke et al., 2003). The increased sediment temperatures in winter due to thermal pollution should markedly increase bacterial metabolism, with a probable decrease in dissolved oxygen content (Boylen & Brock, 1973).

Currents and mixing

The processes governing currents in lakes differ significantly whether ice is present on the lake or not. The ice cover reduces heat losses to the atmosphere and prevents direct generation of wind mixing. In the absence of mixing induced by direct contact between the water surface and the atmosphere, four types of currents can be identified in lakes during the Ice cover period (Bengtsson, 1986 & Bengtsson et al., 1996). These are:

1. Direct flow from a river to the lake
2. Oscillating currents (seiche type)
3. Density currents due to heat transfer from sediments, and finally
4. Convective mixing due to solar radiation through the ice cover

The most obvious one would be the direct inflow from a river basin into the lake. These currents are recognizable and measurable only if the river is large and the lake is narrow (Malm et al., 1998).

When the wind acts on an ice cover, the ice cover as well as the water surface is tilted, which will introduce the second type of currents known as the oscillating currents (seiche type). The oscillation takes place when the wind ceases to blow and there is adjustment of the ice and the water surface. However, oscillations are superimposed also on a stationary tilting surface. Depending on the morphology of the lake and the wind conditions, the period of such oscillations can make water particles move back and forth over short distance. These oscillating currents are the most pronounced currents during the ice-covered period with typical velocity amplitudes of millimeters per seconds and occasionally increasing to centimeters per second.

During the ice-free period, from summer to winter, heat is stored in the bottom sediments. Then throughout the winter heat is released to the water. In an ice-covered lake the heat loss to the atmosphere is reduced, resulting in increased water temperature during winter. Bottom water, which gains heat from the sediments near the shores, moves along the bottom towards the deeper parts of the lake which usually have a temperature below 4°C (temperature of maximum density) in the main part of the lake. The heated and thereby denser bottom water near the sloping shores moves along the bottom toward the deeper parts of the lake. This type of current at the bottom of and along lake sides is generated by heat transfer from sediments (Hutchinson, 1957; Mortimer & Mackereth, 1958). A review of previous investigations on density currents (Malmo et al., 1998) showed that these currents have small velocities and are not possible to measure in the field by available technology. This led to the use of experimental laboratory trials and indirect methods, such as; tracers (Likens & Ragotzkie, 1965, 1966) and dye (Welch & Bergmann, 1985). The velocity magnitudes for these currents are small, typically on the order of m/day.

During early spring- late winter, when the ice cover is snow free or there is just a thin layer of snow above the ice, shortwave radiations can penetrate the ice cover and heat the water beneath the ice. This will cause a rapid heating of the water close to the ice. A homothermal layer growing downwards develops directly under the ice. Such heating takes place only over a few days. Convective mixing has been described by several researchers; see for instance (Birge, 1927; Woodcock and Riley, 1947; Likens and Ragotzkie, 1965; Farmer, 1975; Matthows & Heaney 1987, Maher & Malm 2003).

Study Site and Measurement

Lake Vendyurskoe

All measurement presented here were conducted in Lake Vendyurskoe, located in the southern part of the republic of Karelia, Russia (latitude 62°10′N, longitude 33°10′E). The lake has a watershed of about 82.8 km^2. The lake has three small inflows, and one outflow. The lake hollow has a glacial origin and its main axis is directed from west to east. The lake has a length of 7 km and a maximum width of 1.5 km. The maximum and mean depths are 13.4 and 5.3 m respectively. The lake area is 10.5 km^2, and the water volume at mean water level is 5.5×10-2 km^3. The geometrical dimensions and bottom topography of the lake are given in Figure 1**.** A more thorough description of the lake as well as previous winter studies conducted there as mentioned earlier are given in the reports by Bengtsson et al.; (1995) and Malm et al.; (1997). Lake Vendyurskoe located in the southern part of the Republic of Karelia, Russia. The bottom sediments consist mainly of silt and the upper layer of the sediments (0.4-1.0 m), containing organic mud, has a water content of 80-95 %.

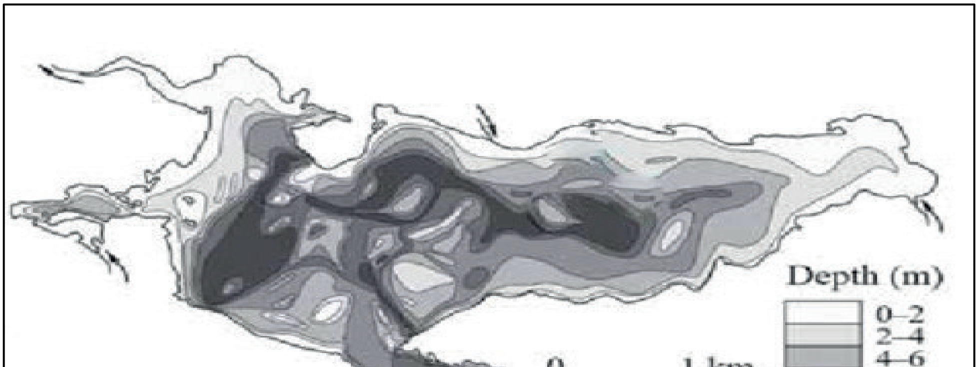

Figure 1 Bottom topography and geographical dimensions of Lake Vendyurskoe.

From an ecological standpoint Lake Vendyurskoe is a mesotrophic lake. The water transparency is high and the corresponding typical Secchi disk reading in the lake during the ice-free period is 3-4 m. Hydrological and morphological data of lake Vendyurskoe are presented in Table 1.

Table 1 Hydrology and morphology of Lake Vendyurskoe

Parameter	Value
Surface area (km^2)	10.4
Drainage basin area (km^2)	82.2
Lake percentage of watershed (%)	12.7
Water volume (mean water level) (km^3)	0.055
Maximum depth (m)	13.4
Average depth (m)	5.3
Length (maximum) (km)	7
Exchange coefficient (for 1 year)	0.3

Lake Velen

The hydrology of the Lake Velen basin was intensively investigated in the late 60's and 70's, Falkenmark (1973). Lake Velen is situated in south-western Sweden. It is surrounded by forest of boreal type. The local climate tends towards a local-continental type with low temperature and much snow in the winters. The daily mean temperature is below -10°C during more than 10 days during a winter. Ice usually forms in December and disappears in April. The river inflow is almost zero during the ice covered period.

The lake has a glacial origin. The bottom sediments are postglacial sandy clays overlain by muds. The sediment on shallow water is silty with less organic content than the sediment on the deep waters. There is sand bottom only very close along the eastern shoreline. The lake basin itself is elongated, 6.3 km long, and width 1.1 km. The lake area is 2.8 km^2 and the mean depth 6.5 m with maximum depth 17 m. The western shoreline is rather steep. The topology of the bottom is regular with no depressions. Detailed morphometric properties of the lake are given in Falkenmark (1973).

Extensive measurements of the thermal regime and mixing conditions, Falkenmark (1973), have been carried out including simulations of currents, Bengtsson (1978), and temperature development, Svensson (1978). With relation to winter conditions, continuous temperature measurements were made in four verticals during 1969-1972. The DO was measured by taking samples (from near the surface, at 1 m, 2 m, and then every 2 m downwards) once a month in a vertical in the central part of the lake.

Measurements on Lake Vendyurskoe

The first study of thermal regime of Lake Vendyurskoe was made between 1978 and 1980. Water temperature and temperature in the upper 1.5 meters of the bottom sediments were measured in one vertical in the central part of the lake. Since then, several field work and publication had Lake Vendyurskoe as their scope during the ice cover period (see Malm, 1995, 1998, 1999, Malm et al 1997, 1998; Bengtsson et al 1995; Maher et al 1999, 2003, 2004).

These studies can be divided into three categories: the time of formation of the ice cover, mid-winter with stable ice cover and ice breakup period during early spring. The studies can be classified further into four topic categories; studies on ice cover growth and decay. This would include meteorological factors and their relation to ice cover period length, different types of radiation, and heat conduction to and from the ice sheet. The second study category was dedicated to temperature and thermal regimes. Currents, mixing and spring convection represented the third type of studies. Finally, many studies were dedicated to observations, analysis and modeling of DO during the full ice cover period.

Systematic and annually based field investigations started as early as 1994 and continued for two decades by many researchers, who later presented data collected by themselves or the accumulated data from various field investigations campaigns. Water temperature was measured continuously from the time of ice formation since 1996. Lake site field campaigns were performed during the winter 1996/1997 and 1997/1998 concentrating on late winter conditions. The location of measurement station is shown in Figure 2. The continuous temperature observations were done at station 4-8. For the registrations of the temperature dynamics at the sediment-water interface, a thermistor chain with narrow spacing between thermistors was installed at station 4-8. The sensor positions depths were -1.15, -0.85, -0.55, -0.35, -0.20, -0.10, 0, 0.10 and 0.20 meter. Temperature registrations were conducted each third hour during the entire period.

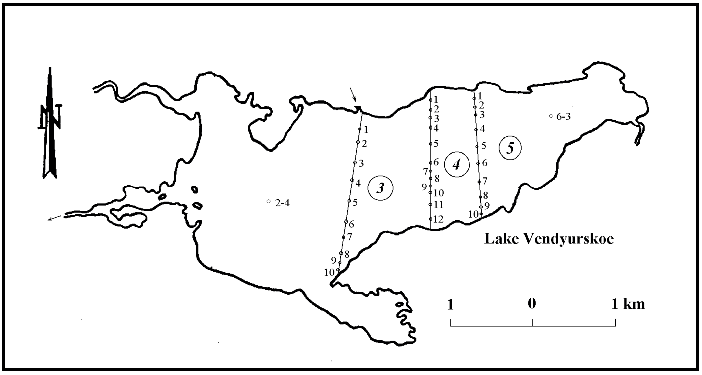

Figure 2 Location of measurement stations in Lake Vendyurskoe during the winter of 1996/1997, during the following winter (1997-98) only section 4 was used.

The holes in the ice cover were covered directly with a plastic cover after taking measurements to avoid contact with the atmosphere.

Measurements of net currents were made along cross-section 4 on 19-23 December 1996, and 22, 24-26 April 1997 using the acoustic current meter. The averaging time of the current measurements corresponded to a multiple of seiche periods to ensure that the influence of oscillating currents on the mean current determination was marginal. Devices capacities are for all measurements during the all presented surveys are summarized in Table 2.

Table *2* Capacities and characteristics of measurements equipment used in field measurements included in this study

Device	Parameter	Range	Accuracy	Resolution	Response time
Temperature profile recorder, TR-1	Temperature - 11 channels (°C)	-2.46..+2-1.48	±0.15	0.02	3.5 min
TCD profiler	Temperature (°C)	0..25	±0.05	0.003	0.1 s
	Conductivity (μS·cm-1)	10..50	±3%	0.2%	0.1 s
		10..1000	±10%	3%	0.1 s
	Depth (m)	0..20	0.1%	0.001	0.001 s
Acoustic current meter	Current velocity, 2 components (cm·s-1);	-7..+7	±40%	0.02	5 s
	Instrument orientation (deg)	0..360	±10	2	5 s
Pyranometers	Solar radiation (W·m-2)				
1)Normal		0..1000	1+10%	1	5 min
2)Submergible		0..200	0.3+20%	0.2	5 min
Temperature and DO device WTW OXI 340 Oxygen meter and CellOx®	Temperature °C and dissolved oxygen mgl-1	NA	±0.05 % for Do and ± 0.1 k for temperature	NA	NA

Note: The temperature profile recorder and pyranometers were developed by Aanderaa Instruments, Norway, and the acoustic current meter by Ekran, Russia and Oxygen meter was provided by WTW, Germany. All other instruments have been developed at the Northern Water Problem Institute, Petrozavodsk, Russia.

Results

Ice and snow thickness

From long time early studies on Lake Vendyurskoe (see for instance Malm et al,. 1997; Maher & Malm 2003), it is found that the ice cover mostly forms during early/mid-November. After the formation of the ice cover, ice continues to grow on the lake through most of the winter. In Lake Vendyurskoe the ice usually breaks up between 8 to 20 May (Maher & Malm 2003).

This study presents measurements of snow depth and the development of the ice thickness throughout the winter on Lake Vendyurskoe from 1994 to 1997 and late winter of the year 2000. Measurements showed that the formation and breakup of ice dates are representative of many of the lakes in this latitude. The ice formation takes place usually in November (Malm et al,. 1998; Maher & Malm 2003; Maher et al., 2005). However, in 1996 ice formed on 12 December. Due to internal melting and tension within the ice, the ice cover usually cracks when the ice cover is snow free, even when the ice is more than a decimeter thick. It is important to adapt a definition for ice break-up date; here the date when the lake is totally free from ice cover is the date of break-up.

Ice evolution and break-up

The length of ice covered period and the ice cover characteristics are directly influenced by climatic conditions. These parameters were measured almost in all field measurement campaigns. Data obtained from direct measurements made it possible to follow the evolution of the ice cover during the winter period and to examine the influence of climatic conditions. Using climate data from Petrozavodsk weather station (61.77° N 34.32° E) on average air temperature and snow depth, the linkage between the ice cover characteristics and these two climate variables could be verified.

For not very large lakes and after the establishment of a stable ice layer on the water body, ice cover thickness evolvement can be determined using Stefan's (Equation 1). Using negative air temperature, snow status on the ice cover as an indicator for ice growth and a value for the degree day constant between 2 to 3.5, a good agreement between estimated and direct measurement values could be obtained for both years, Table 3.

Combining direct measurement and calculated values for ice and snow thickness, ice and snow cover profiles could be developed for whole winter seasons from 1994-99, except for the winter of 1997-98, see Figure 3. Examining the characteristics for the ice cover during these winters, it was observed that the ice cover formation on the lake used to take place between November and December depending on local weather conditions.

Table 3 Measured and calculated values for ice cover development on Lake Vendyurskoe for two winters. The degree day (C) coefficient in Equation (1) was set to 2 in 1995-96 due to the presence of snow during almost all winter. Same value was used for early winter of 1996-97 and 3.5 was used in mid to late winter cause the ice cover was almost free from snow.

Winter 1995-96			Winter 1996-97		
Date	Ice thick. measured	Ice thick. calculated	Date	Ice thick. measured	Ice thick. calculated
8-Nov	0	13	1-Nov	0	0
26-Nov	14	20	12-Dec	0	8
27-Nov	17	21	18-Dec	7	16
25-Dec	41	41	19-Dec	12	18
20-Mar	69	71	20-Dec	16	18
21-Mar	65	71	23-Apr	61	59
16-Apr	77	72	27-Apr	60	54

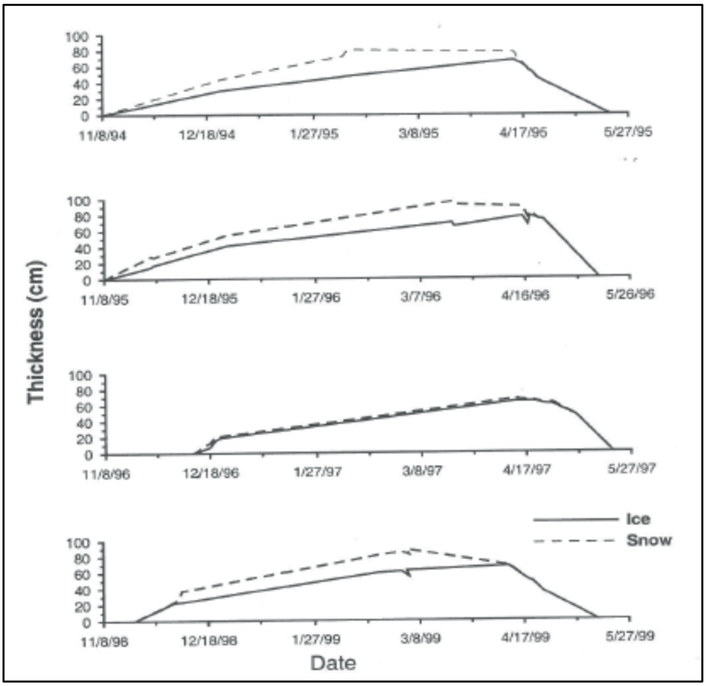

Figure 3 Ice and snow thickness at Lake Vendyurskoe during 4 years of measurements

Data on air temperature and snow depth during both winter seasons of 1995-1997 are presented in Figure 4. These two winter seasons witnessed different climatic conditions prior to ice formation and throughout the whole winter.

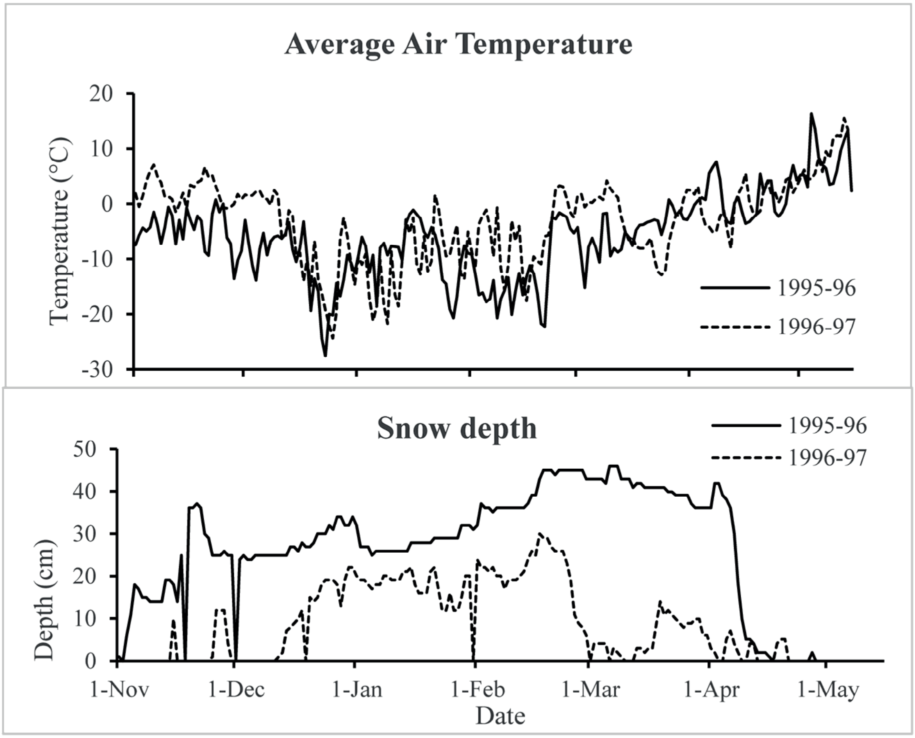

Figure 4 Air temperature and snow depth data from Petrozavodsk meteorological station for the winters of 1995-1997

In November 1995, the temperature was well below 0 °C since the beginning of the month (- 7.5 °C on 1st of November) and exceeded 0 °C not until late March. Snow was present during the whole month of November with depth between 20 to 30 cm. Temperature and snow conditions led to an early start of the ice cover, on 8th of November, on Lake Vendyurskoe. The maximum average ice thickness on Lake Vendyurskoe during this year was 77 cm and was registered on the 23rd of April. However, the 1996-97 winter season witnessed opposite climatic conditions, where temperature was above 0 °C during whole November and little snowfall, so stable ice was formed on Lake Vendyurskoe by mid-December and maximum ice cover depth was around 60 cm by mid-April.

In Northern Hemisphere, the NAO have a pronounced effect on climate and hence on all processes in ice covered lakes (Maher et al., 2005). The NAO is usually presented in a dimensionless index NAOI, positive winter values of NAOI are associated with strong westerly winds that transport warm, moist and maritime air across northern Europe, giving rise to mild wet winters, while low NAOI values correspond to weak westerlies and cold dry winters in northern Europe (Straile et al. 2003).

Examining climatological conditions for two years, 1994-95 and 1995-96, marked by a strongly positive NAOI of 3.96 followed by a strongly negative NAOI of 3.78. This was reflected in a thicker ice in 1996-97 winter than that of 1994-95, specifically prior to ice break up as observed values showed that the ice cover thickness was about 60 cm in 1995-96 compared to more than 70 cm for 1995-96 (Maher et al., 2005). The same study reported that the ice cover period didn't vary much between these two winters with opposite NAO values.

The date of ice break-up did not vary much; it occurred in mid-May, between 8 and 20 May. The length of the ice-cover period was on average 182 days, i.e. about 6 months. The longest ice period during the campaign was 193 days recorded during the winter of 1994-95, and the shortest period 159 days in 1996-97 winter. During ice formation the water column was characterized by a weak stable stratification and an average temperature of very little above 0 °C.

Lake water temperature development

Directly before the formation of the stable ice cover over the lake, the average water temperature of lake water is at its minimum value, of about 0.3-0.5°C. The average water temperature after the formation of the ice cover continues to increase (except close to the ice cover) throughout the winter (Maher and Malm 2003). Air temperature and water temperature profile prior and during ice formation at a full cross section of Lake Vendyurskoe during the two winter seasons of 1994-1996 are presented in Figure 5. In November 1994, initial water temperature was about 1.5 °C and almost 3.5 °C by the end of November. The following winter, the ice formed on the lake on almost the same day, 8^{th} of November. However, initial water temperature was less than 1 °C and the average water temperature was about 4 °C above the sediment by the end of November. The sediment initially must be warmer. Cold water and warm sediment mean large heat flux from sediment to water.

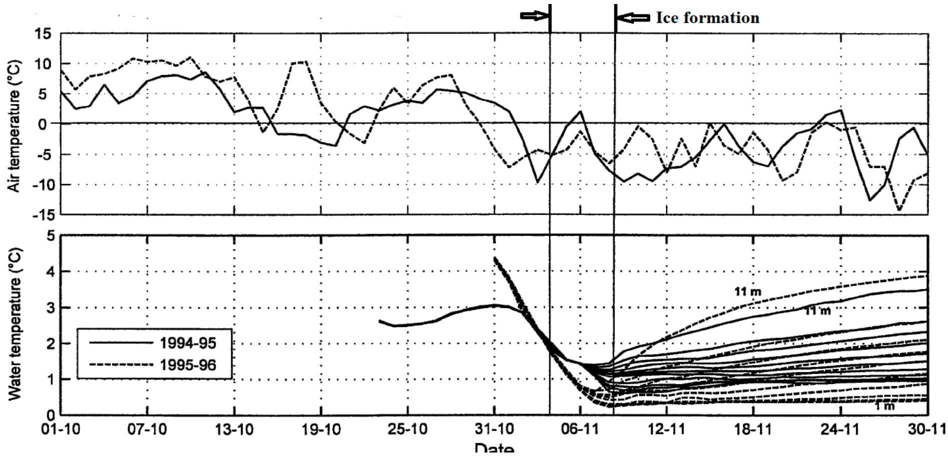

Figure 5 Air temperature, and thermistor chain recording prior to and at ice formation in Lake Vendyurskoe for two winter seasons of 1994/95 (dashed line) and 1995/96 (solid line). The numbers above the line indicate the sensor depth. Sensors were placed 1 m apart.

The increase in temperature is very rapid during early winter and slower in mid-winter. In late winter- early spring period, solar radiation penetrating the ice cover becomes more pronounced and leads to convective mixing of the water column and increase in the heat budget of the lake as well. The development of vertical temperature profile throughout the winter at a station in the middle of cross section 4 is presented in Figure 6. The winter of 1996-1997 had a dry condition with little or no snow on top of the ice cover throughout the winter. Ice formed late, by mid-December, in April spring convection developed rapidly and the convective mixing layer developed from less than 3 m on 1st of April to 5 m by 24th of April.

The development of water temperature profiles measured by a thermistor chain a long a full cross section in the winter of 1996-97 is presented in Figure 7. During the winter period from January to April the temperature continues to increase, but at a slower rate and more homogeneously over the water column compared to early winter. A pronounced vertical stratification is established, with an almost linear temperature increase with depth. In mid-April, the layer with temperatures above 4°C extends from the deep bottom part up to 8-10 m depth.

From mid-April until ice break-up, solar heating is the dominant heat source and heating of the surface waters occurs. Convective mixing is initiated resulting in a homothermal layer. This temperature homogeneous layer thereafter increases in thickness until ice breakup. Heat fluxes at ice-water interface.

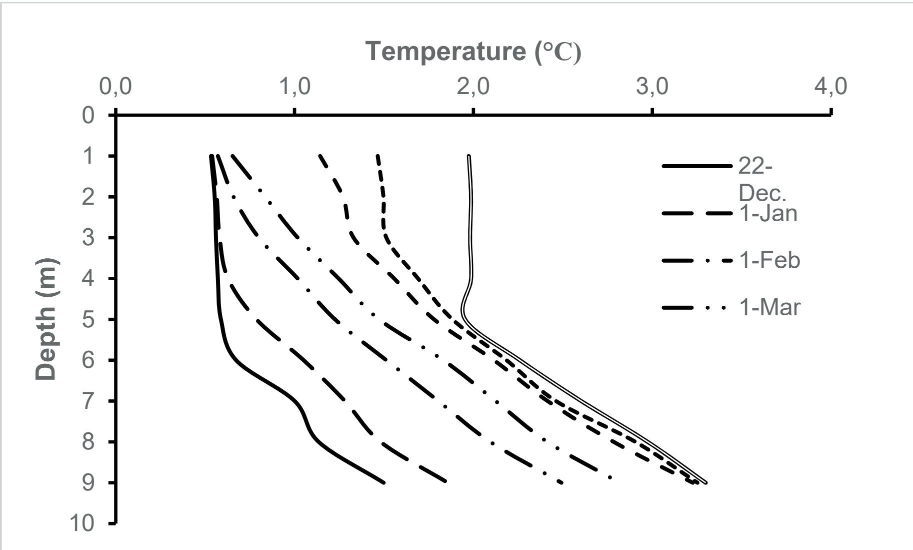

Figure 6 Temperature development throughout the winter of 1996-97 at a station in the middle of section 4. Ice formed by 16 December and by 27 May.

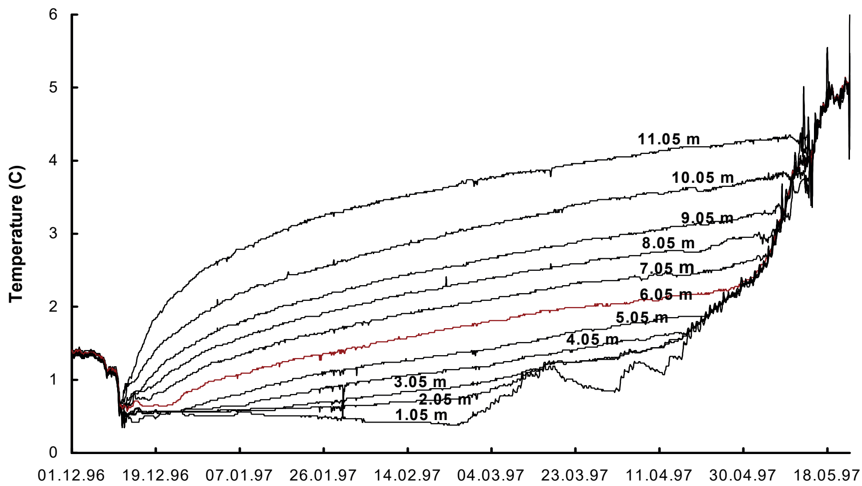

Figure 7 Thermistor chain recordings in full vertical at station 4-7 during the period December 1st, 1996 to May 21st, 1997. The ice formed on December 12 and broke about May 20th. The bottom depth is 11.35 m.

Solar radiation

In Lake Vendyurskoe, the amount of solar radiation that penetrates down to the water is small in early and mid-winter as the ice is covered with snow and the solar intensity is low in winter (Maher & Malm 2003). In comparison with other boundary heat fluxes, solar radiation may be neglected during this time period (see by Malm et al., 1997; Bengtsson et al., 1995). However, in late winter, when the snow cover has vanished, solar radiation is the dominating heat input into the lake. This heat flux causes development of convection, which is by far the most efficient mixing process experienced during the lake's ice-covered period. In order to get a direct measure of the radiation flux magnitude during the late winter period, measurements were made of direct and reflected solar radiation as well as of the amount of radiation penetrating through the ice in April 1997. The solar radiation was registered with 2-minute intervals in April 1997 at a different location on the lake ice cover. An example from April 1997 campaign for two weeks measurements, 14-27 April, of direct, reflected and solar radiation penetrating the ice cover are shown in Figure 8.

During these two weeks the ice thickness was about 60 cm and almost free from snow, except some parts with maximum snow depth of 1-2 cm. During these two weeks the albedo decreased from 0.8 to 0.5 and the amount of radiation penetrating the ice to the water body increased from values close to 1-2 Wm^{-2} to more than 15 Wm^{-2} by the end of April. There is also a spatial variation in surface albedo; Figure 9 shows direct and reflected solar radiation at two locations in Lake Vendyurskoe in the same day.

Figure 8 shows a clear variation in the reflected portion of the radiation depending on the ice cover surface. The incident solar radiation at the two locations were almost the same with a peak at mid-day with a maximum value of around 650 Wm^{-2}. However, the reflected radiation varied from almost 300 Wm^{-2-} at one location to a maximum of 200 Wm^{-2} at the same time of the day, which means that the albedo varies between 0.3 to 0.45.

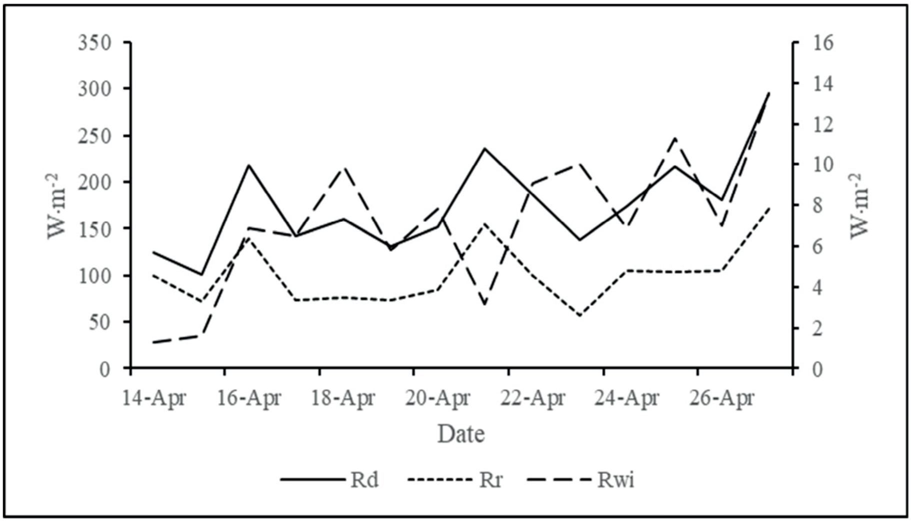

Figure 8 Daily averages of measured incident and reflected solar radiation (Rd, Rr), radiation at the ice-water interface (Rwi, left axes), during the period April 14-27, 1997

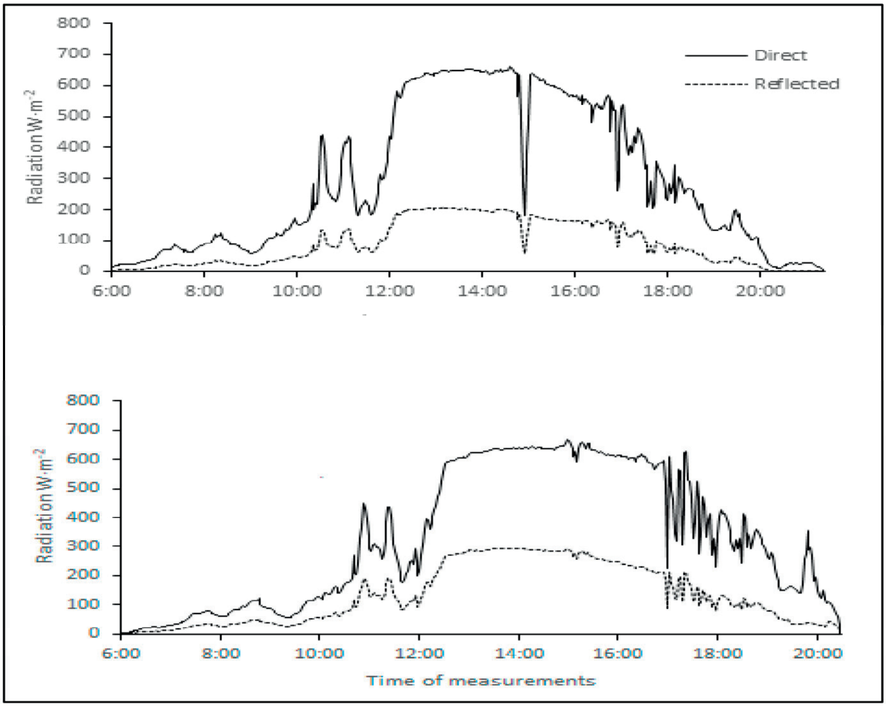

Figure 9 Direct incident and reflected solar radiation on Lake Vendyurskoe on the 1st of May 1997 at two different locations of the ice cover.

Heat conducted from water to ice

The rate of heat conduction from water to ice is estimated from the temperature gradient in the vicinity of the ice (dT/dz) and the molecular conductivity for water at 0°C (λ=0.569 W·m-1·°C-1) using the gradient method,

$$Q_{wi} = \lambda \frac{dT}{dz} \quad (4)$$

The temperature gradient was estimated from measurements in the vicinity of the ice (see Figure 5), as the average gradient within a 10 cm layer beneath the ice. The use of the molecular value on conductivity for the heat flux calculation has been motivated by Malm et al., (1997). During early and mid-winter, the mean rate of heat conduction from water to ice is relatively stable and in the range 1-2 $W{\cdot}m^{-2}$. Example of profiles during early winter period is shown in Figure 10. During late winter the rate of heat conduction to the ice increases and reaches values of about 4-5 $W{\cdot}m^{-2}$. The temperature gradient is steep. The temporal variation for the conductive heat flux, as determined from temperature profiles measured by the thermistor chain at station 4-11 is given in Figure 11.

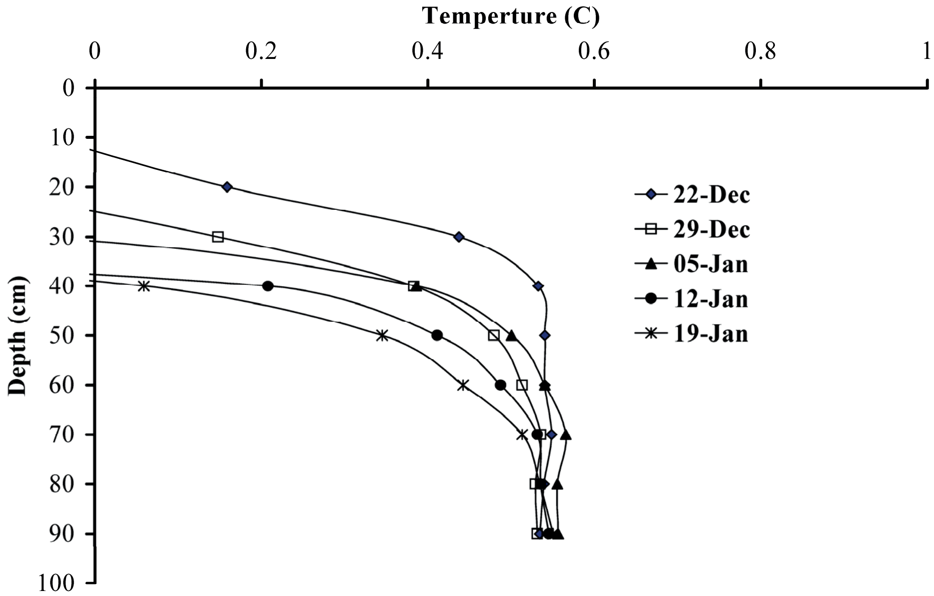

Figure 10 Vertical temperature structure in the vicinity of the ice, obtained from thermistor chain recordings in the winter 1996/97, at station 4-8 during early-winter.

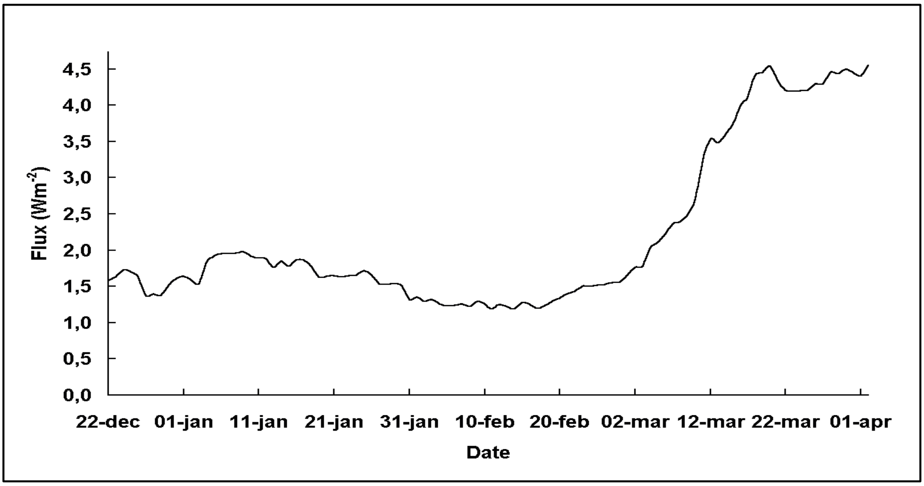

Figure 11 Conductive heat flux from water to ice at station 4-8 during the period 22 December to the first of April 1997. Flux estimation based on thermistor chain recordings in the vicinity of the ice.

Sediment heat flux

After the formation of a stable winter ice cover, the lake water body is almost thermally isolated from the atmosphere. During the whole ice covered period heat conduction from the sediment becomes very significant for the thermal budget of the lake, and this flux is normally the main heat source in early and mid-winter in an ice covered lake (Bengtsson & Svensson 1996).

Continuous measurements of water temperature along the water-sediment interface were performed during almost all winter measurement campaigns on Lake Vendyurskoe. At deep parts the temperature profile at the sediment water interface is characterized by a linear temperature decrease. This decrease was observed through the upper part of the sediment and more than half a meter into the water column. Above the sediments in shallow parts of the lake there is a constant temperature gradient with decreasing temperature in a layer of about 10 cm thick above the sediment-water interface. Example of these two profiles (Maher & Malm 2003), are shown in Figure 12.

Heat flux from sediment to water was calculated using the same formula to estimate heat flux as for water to ice, see equation 4. Sediment conductivity, λ, was estimated from values of porosity and quartz content using a method proposed by Johansen (1975),

$$\lambda = \lambda_w^P \, \lambda_s^{(1-p)} \qquad (5)$$

$$\lambda_s = 7.7^q \, 2^{(1-q)} \qquad (6)$$

where λ is conductivity, p is porosity, q is quartz content, and the subscripts w and s stand for water and sediment, respectively. The high water content in the upper layer of sediments resulted in conductivity values close to that of water, being on average about 5% higher. This approach was tested by Sundberg (1986) for various types of soils and was found to give a good agreement. The type of sediment, porosity and content of organic material of the upper 10 cm sediment layer were determined at the stations along cross-section 4 in Lake Vendyurskoe.

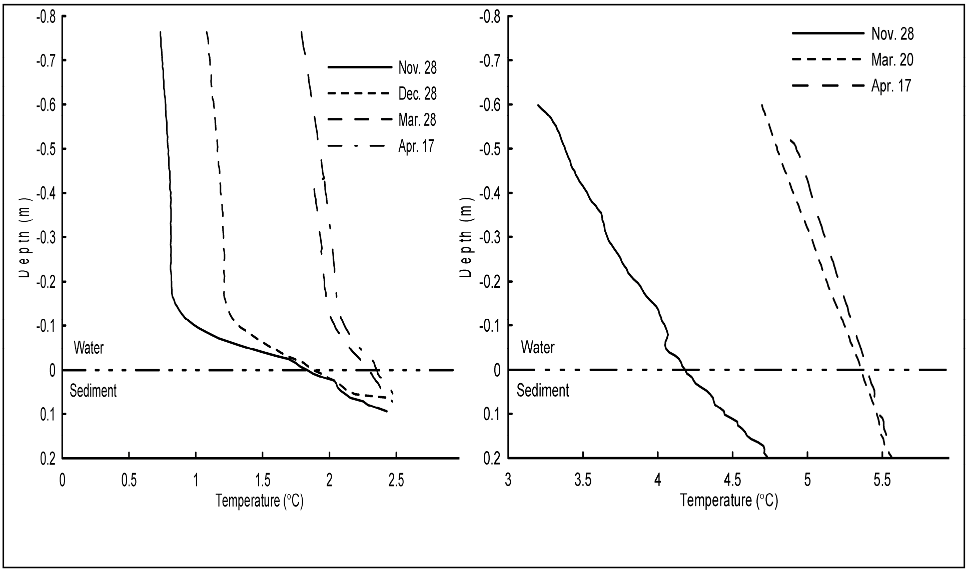

Figure 12 Vertical temperature structure at the water/sediment interface at a shallow water station (left) and at a deep water station (right) in the winter 1996/97.

Data collected showed that the heat flux from sediment to water is depending on both, bottom depth and time after ice formation. The heat flux is higher in shallow regions of the lake than the deep ones since the sediments are warmer and the water colder at shallow waters.

The calculated heat flux magnitudes for three year at a middle cross section in Lake Vendyurskoe are presented in Figure 13. The heat flux is rapid during early winter and continue to decrease throughout the whole winter period with maximum values are registered directly after ice formation. The sediment heat flux after ice formation varied from year to year, being 4.6 W·m-2 during the winter 1995-96 (ice formed by 8th of November) and 1.9 W·m-2 during the winter 1998-99 (ice formed by 28th of November). Average heat flux for the winter period during three years at the same measuring station is presented in Table 4. During December 1998 the values of heat flux varied from 4.1 W·m-2 at a depth of 4.1 m, to 1.2 W·m-2 at a depth of 11.55 m.

Table 4 Average calculated values for heat flux at the sediment water interface Qsi (W/m2) at a station in the middle of Lake Vendyurskoe for three consecutive years

Year	Month				
	December	January	February	March	April
1995-96	3.26	2.28	1.75	1.43	1.18
1996-97	3.71	2.42	1.77	1.29	0.37
1998-99	1.67	1.35	1.06	0.88	0.58

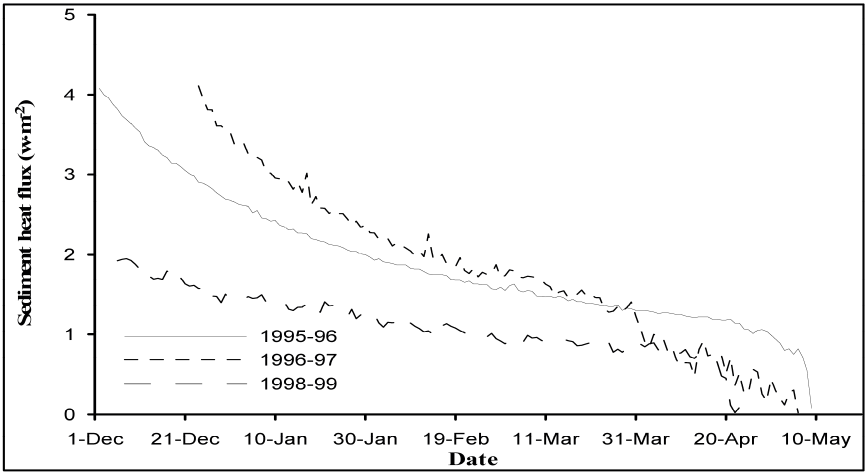

Figure 13 Average heat flux from sediment to water during three years at the same measurements station at the middle of cross section 4 (bottom depth 11.4 m) in Lake Vendyurskoe.

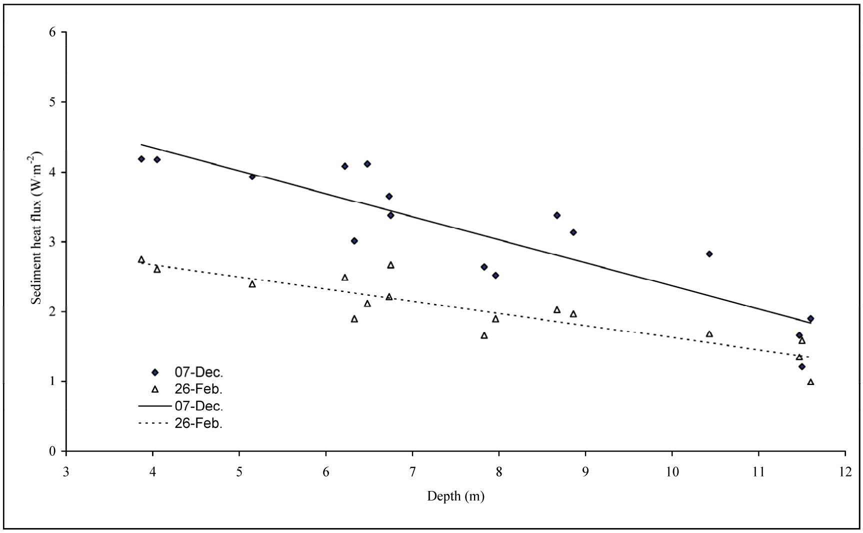

Figure 14 Measured (points) sediment heat flux during the two surveys vs. bottom depth during the winter 1998-99. Linear regressions (lines) for each survey, illustrating the bottom depth dependence are also shown.

Dissolved Oxygen

At the time of ice formation, the lake water is almost 100% saturated and almost homogeneous over the water column. The DO concentration at the upper layer of the water column shows little or no reduction through the winter period, except during early spring mixing (Maher et al., 2004). Meanwhile, the DO concentration in near-bottom layers and sediments gradually decreases because of the Sediment Oxygen Demand (SOD), and the consumption by bacterioplankton. The reduction in the overall DO content of the lake and the evolvement of the vertical DO profiles throughout the winter, except for the convective mixing period in spring, can reasonably be well quantified by accounting for SOD only (Bengtsson and Maher 2020). Lake bottom morphology affects the sediment surface area and that leads to inhomogeneous ratios of sediment area exposed to water in relation to water volume at any given depth of the lake bottom. The DO concentration remains high near the surface but drops to low values at large depths, where the ratio volume/ wet perimeter, i.e. the hydraulic radius, is small, see Figure 15. This illustrates the importance of lake morphology on the DO consumption and hence the DO vertical profiles during the ice covered period (Bengtsson and Maher 2020).

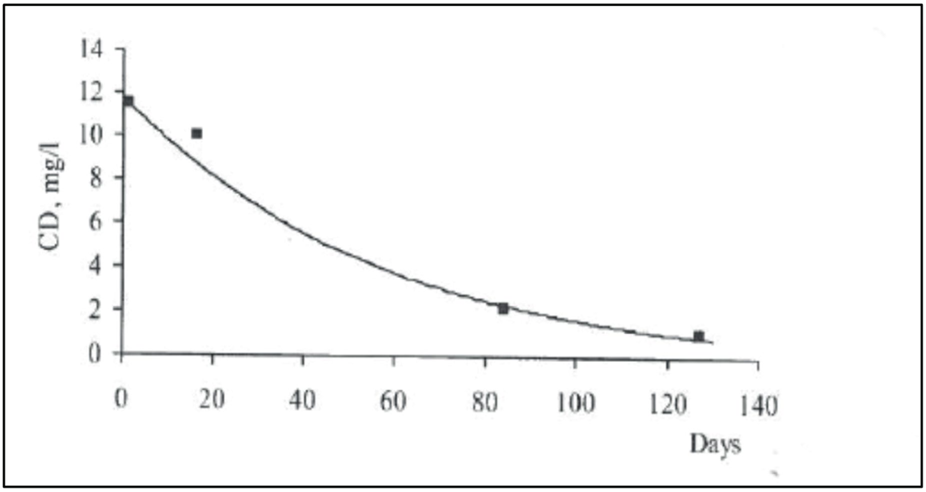

Figure 15 DO concentration in bottom layers in Lake Vendyurskoe during winter 2001-2002 at one station. Line stands for simulations, squares for observational data.

The first survey of the DO presented in this thesis was conducted in April 2000 to examine the effect of spring convection on the DO distribution during the mixing process. DO was measured in a full cross section on Lake Vendyurskoe from 13th to 21st April. An example of the dissolved oxygen distribution over the cross section is shown in Figure 16. The dissolved oxygen is horizontally well mixed. Away from the shores, in the vertical direction, all oxygen profiles are almost identical. Beneath the ice cover, in the top layer of the water column, the dissolved oxygen content was relatively high ranging between 10 to 13 mgl-1 at all measurement points, with almost 90 % saturation. Four different dissolved oxygen profiles at different measurement stations representing different bottom depths are shown in Figure 17. The dissolved oxygen content is very low near the bottom, regardless of the bottom depth. It drops over a very short distance to zero or to values close to zero.

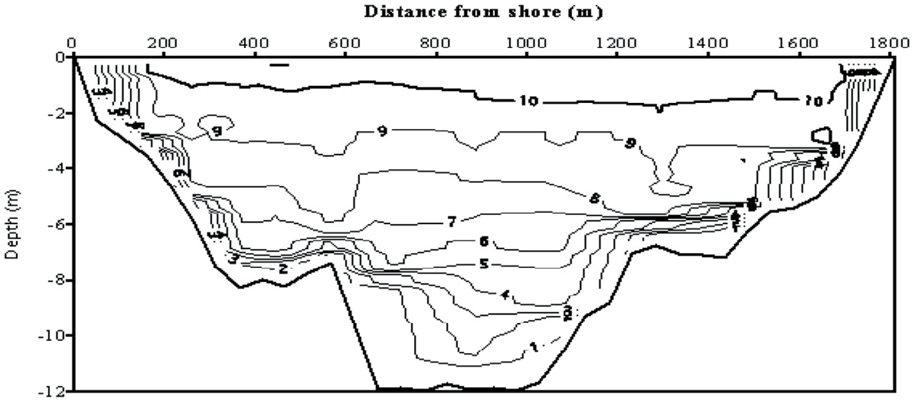

Figure 16 Dissolved oxygen distribution at cross section 4 in Lake Vendyurskoe on 20 April 2000

Through the seven days of investigation there was no snow on the ice cover. Solar radiation could penetrate the ice cover and heat the water below. The temperature of the water increased, and a mixed layer developed. In Figure 17, a profile of the water temperature variation during the investigation period is presented. Thermal convection already started a few days prior to the dissolved oxygen measurements. The thermal convective layer grows from 1 m to 5 m over the period April 13 to April 21. The temperature of the convective mixing layer beneath the ice cover was 1.0 °C when convection was initiated and about 1.5 °C at the beginning of oxygen measurements. The temperature of the Mixed Layer continued to increase until it was more than 2 °C at the end of investigation period. The bottom layer temperature hardly experiences any changes through the investigation period. The water temperature profile and the DO distribution change due to the radiatively induced convection are illustrated in Figure 18.

There is a homothermal 4 m deep layer within which DO is constant. Do has decreased over 4 days. However, the oxygen below the mixed layer remains constant. Thus, there is no downward transport of oxygen into the deep water. Instead there must be loss of oxygen to the sediments. Because of the convective mixing, oxygen can reach the water-sediment interface where it is consumed.

The oxygen below the Mixed Layer remains constant. Thus, there is no downward transport of oxygen into the deep water instead there must be loss of oxygen at the bottom. Because of the Convective Mixing, oxygen can reach the water-sediment interface where it is consumed.

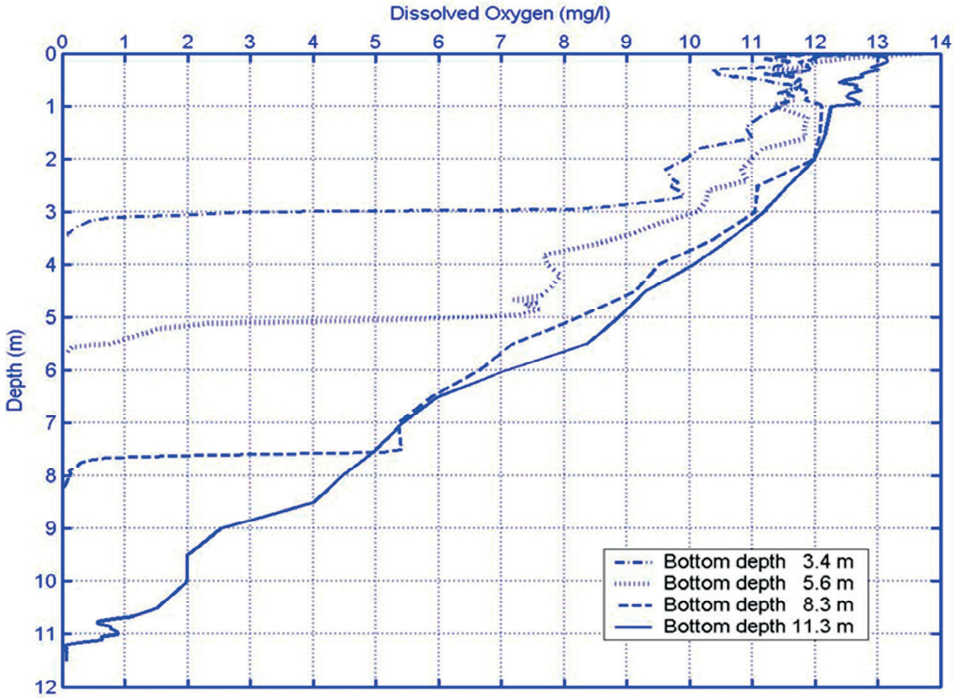

Figure 17 Dissolved oxygen concentration (mg/l) at four different measuring points with variable depths on 17 April 2000 at Lake Vendyurskoe, all measurements were taken from the underside of the ice cover.

The oxygen below the Mixed Layer remains constant. Thus, there is no downward transport of oxygen into the deep water instead there must be loss of oxygen at the bottom. Because of the Convective Mixing, oxygen can reach the water-sediment interface where it is consumed.

In the present study the rate of oxygen consumption through the lake sediments was estimated from the reduced oxygen content in the water volume at a full cross section on the lake divided by the bottom area reached by the mixing layer within this section. The rate of dissolved oxygen consumption in the sediment during this period was about 0.156 g O2 m-2 day^{-1}.

The oxygen uptake by lake sediments as a result of mixing has been reported by many researchers. Hargrave (1969), while working on undisturbed samples from Marion Lake, British Colombia found that gentle stirring significantly increased oxygen uptake by sediments, especially if the dissolved oxygen concentration was below 6 mg l^{-1}. He also concluded that the increase of water temperature above the sediment increases significantly with the increase of the rate of oxygen consumption by benthic communities. The same conclusion was reported by Carey (1967). Carey's experiment on sediments from Long Island Sound sediments was usually conducted with water containing less than 6 mg l^{-1}.

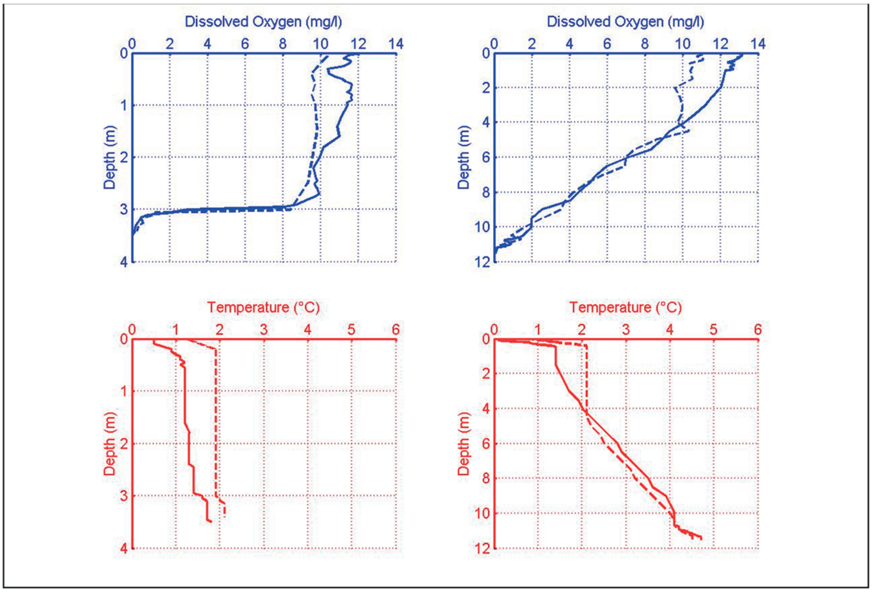

Figure 18 Dissolved Oxygen concentration (mg/l) and temperature profile at station 4-1 (left, bottom depth 3.4 m) and station 4-8 (right, bottom depth 11.4 m) in Lake Vendyurskoe on 17 April 2000 (solid line) and 21 April 2000 (dotted line).

Currents and mixing

Oscillating Currents are generated by wind action on the ice cover, causing it to tilt and oscillate (Malm et al., 1998). These currents are in the magnitude of mm/sec to cm/sec and have an oscillation period in agreement with the Seiche period estimated in a later study by Malm, (1999) for the same lake.

Measurements of net currents were made along cross-section 4 on 19-23 December 1996, and on 22, 24-26 April 1997 using the acoustic current meter. The results from the mean current measurements in December 1996 and April 1997 are given in Figures 19-20. In general, the mean current velocities have a magnitude of about 2 mm·sec^{-1}. The maximum values were registered at a depth of 2-3 m below the ice. During the December survey (1996) at station 4-9, this maximum velocity was rather high, being ~7 mm.sec^{-1}. The smaller velocities registered in the vicinity of the ice and the bottom indicates the influence of boundary friction. There is also a decrease in mean current velocity magnitudes from the December to the April survey (1997). Generally, the current is directed eastward in the central part of the lake and westward along both shores, suggesting a double-cell circulation pattern. The same circulation pattern was suggested during the previous winters (see Malm et al. 1996), although not as clear.

The mean current magnitude was measured continuously over a period of 8 hours on April 22 at station 4-3 at a depth of 2 meter. The results from this registration are presented in Figure 21. The current velocity magnitude showed no significant changes during those 8 hours, being ~2 mm·sec^{-1} at the beginning and ~1.5 mm·sec^{-1} at the end. The maximum and minimum values recorded during this period were about 3.4 and 1 mm.sec^{-1} respectively. There were no significant changes in the direction of the main current during this period either.

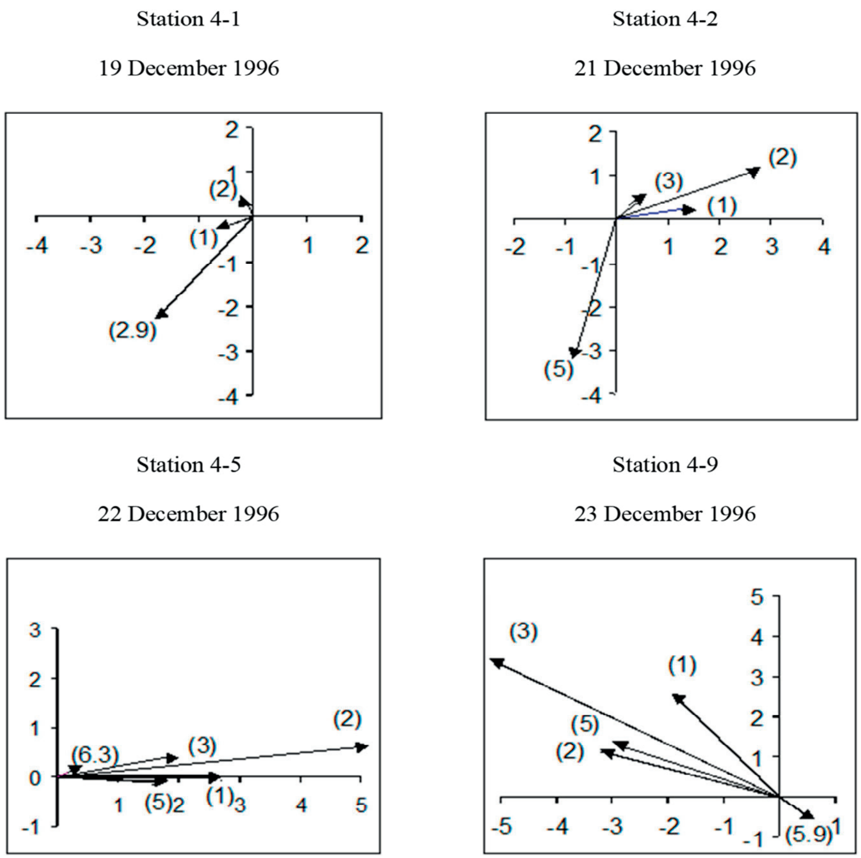

Figure 19 Registered mean current during the December survey 1996 along cross section 4 in Lake Vendyurskoe. Axis numbers stand for velocity in mm.sec-1 and numbers between brackets for depth of measurements in meters.

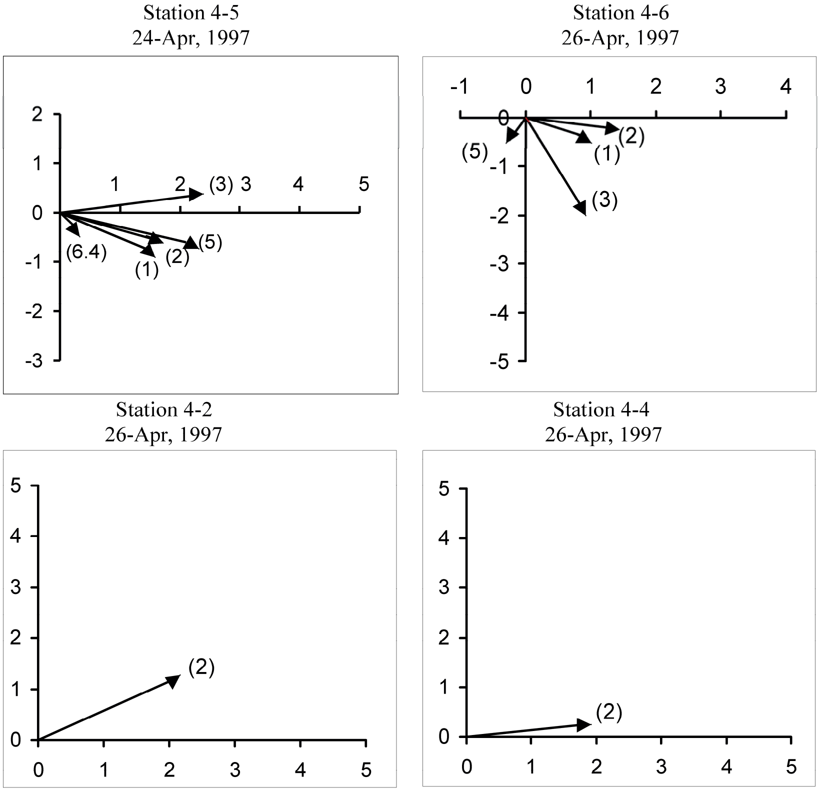

Figure 20 Registered mean current during April survey 1997 a long cross section 4 in Lake Vendyurskoe. Axis numbers stand for velocity in mm.sec-1 and numbers between brackets for depth of measurements in meters.

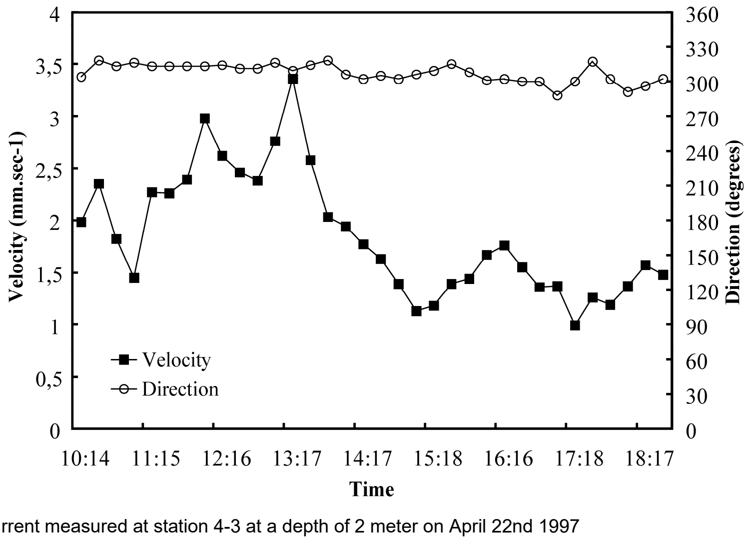

Figure 21 Current measured at station 4-3 at a depth of 2 meter on April 22nd 1997

Conclusions

This thesis summarizes observations mainly for ice covered Lake Vendyurskoe, including ice conditions, thermal regime, dissolved oxygen and dynamics. Direct measurements, historical records and empirical models presented here concluded that: the ice cover period can last between six to seven months with ice maximum thickness ranging between 60 to 80 cm. Examination of the effect of two consecutive years with positive NAOI in 1994/95 and a negative value 1995/96, showed that the negative NAOI was associated with less initial temperature before ice formation. Negative NAOI year was associated with greater maximum ice thickness. Positive NAOI year, due to warmer weather, spring mixing happened earlier than the negative NAOI year. However, the length of the Ice cover period didn't vary much between the two years.

When ice forms early in the winter, the water of the main water body is warmer than when the freeze-over is late. At the time of break-up all water below 8m is 4 °C.

The average water temperature during ice formation, which starts usually between November to December, was 0.5-1 °C in the water column with a little more than zero degrees beneath the ice cover and around 4°C or closer at the sediments. The water body average water temperature during five years of investigation reached a maximum of 2.5- 3 °C by the end of the ice cover period (April-May). Heat flux from water to sediments is increasing directly after the ice formation from early winter to early spring, while opposite process takes place for the heat flux conducted from water to ice. Heat flux from water to ice ranged from 0.5 $W \cdot m^{-2}$ at early winter to an average of 1-2 $W \cdot m^{-2}$ by the end of winter. During the stable ice covered period prior to spring, solar radiation starts to increasingly penetrate the ice cover.

Oscillating currents due to tilting of ice cover by wind forces are the major type of currents in the lake and result in the development of main currents under the lake ice. The averaging time of the current corresponded to a multiple of seiche periods.

Before the formation of a stable ice cover over the lake, DO content is close to saturation and almost homogeneous throughout the water column. The DO content near the ice witnesses very little change throughout the winter. The sediment oxygen demand is the major source of DO depletion throughout the winter, and since the sediment surface area and water volume ratio are dependent on lake morphology, DO reduces with depth. These conditions of DO development under the ice cover change by early spring when solar radiation penetrates the ice cover. DO is redistributed over a homothermal layer growing downwards and at the same time there is a small reduction of the DO concentration above the sediment due to increase of SOD. Soon after with more solar radiation, primary production by photosynthesis increases and the DO is replenished and becomes abundant with vertical mixing caused by convective currents. The DO profiles change and the DO consumption continues to increase due to an increase of the SOD as well.

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