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Observations of ice impurities in some Finnish lakes

Matti Leppäranta[a*], Matti Tikkanen[b], and Juhani Virkanen[b]

[a] Division of Geophysics, University of Helsinki, P.O. Box 64 (Gustaf Hällströminkatu 2), FIN-00014 Helsinki, Finland
[b] Department of Geography, University of Helsinki, P.O. Box 64 (Gustaf Hällströminkatu 2), FIN-00014 Helsinki, Finland; matti.tikkanen@helsinki.fi, juhani.virkanen@helsinki.fi

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Abstract. Ice, snow, and water samples from four lakes and three years were analysed for the impurities (from meltwater). The ice thickness was 30–60 cm. The average concentration of dissolved matter was 11–17 mg/L in ice and 15–23 mg/L in snow. These values were 10–40% of the concentration of dissolved matter in lake water. The sediment content was 2–12 mg/L in all media. The mean metal levels in the ice were 100 µg/L for Al and Fe; 30 µg/L for Zn; 1–10 µg/L for Cu, Mn, and Ni; and below 0.1 µg/L for Cd. These levels were 0.5–2.0 times as high as those in the water. Snowfall is a significant source for many metals. Nutrient levels in the ice were: total-P 2 µg/L; total-N 200 µg/L; SO_4, Na, and Cl 1 mg/L; Ca 2 mg/L; and Mg and K 0.5 mg/L. The levels in the ice were by one order of magnitude lower than in the water. Two river ice sites were sampled for reference. These showed by an order of magnitude higher sediment content than the lake ice.

Key words: lake ice, Finland, impurities, sediments, chemical elements.

INTRODUCTION

Lake ice crystal lattices consist of the pure solid phase of H_2O. The whole sheet of lake ice contains impurities in addition to the ice crystals: gas bubbles, liquid solution, and solid particles or sediments [1]. The impurities account for all substances other than water, including also pollutants. They are stored in the ice sheet, possibly transported due to the drifting of ice, and re-introduced into the water body when the ice melts. Impurities have been studied to some extent in the Arctic sea ice (e.g., [2, 3]), the Baltic Sea ice [4, 5], and river ice [6] but not much in lake ice.

[*] Corresponding author, matti.lepparanta@helsinki.fi

In Finnish lakes the ice season normally lasts from November to May [7]. Impurities accumulate in the ice sheet for most of the ice season and are rejected into the water body during about a one-month melting period. The available literature on these impurities is very limited. Therefore, a field programme was performed in 1997–99 to map pH, dissolved matter, and sediments of lake ice, or rather of the meltwater of the ice, including analysis of metals and nutrients. The lakes are from southern Finland representing different lake types in terms of the water quality. This paper presents the results of the field investigations.

MATERIAL AND METHODS

There are three different types of layers in the vertical stratification of a lake ice sheet: congelation ice, frazil ice, and snow-ice [8, 9]. Thin ice crystal platelets form so-called macro crystals (linear dimensions from 0.1 mm up to 1 m), which optically behave as individual crystals and are normally referred to as such. A lake ice sheet initiates with a primary ice layer. On a calm surface it is very thin (less than 1 mm). Then congelation ice grows down from the ice bottom, and through a 0–5 cm transition zone the crystals become large, often columnar, and their size further increases with depth. In turbulent water, free frazil ice crystals (size 1 mm or less) appear first, and when the buoyancy of these crystals together overcomes the turbulence, they surface and form a solid ice sheet. Frazil ice may also form later in open water spots and be deposited to the ice bottom as fine-grained frazil layers; but in Finnish lakes such layers have not been found. Snow-ice is a mixture of (a) snow and lake water, (b) snow and its meltwater, or (c) snow and liquid precipitation. It grows upward on the top of the ice due to (a) flooding of the ice cover, (b) in melt–freeze cycles, or (c) via liquid precipitation, and the resulting crystals are small as frazil ice crystals. The forms (b) and (c) are also called superimposed ice.

In southern Finland the thickness of ice is at maximum in March, with the annual mean of 50 cm and standard deviation of 10 cm [7]. Snow-ice thicknesses are typically 5–20 cm [9, 10]. The melting of ice takes about one month in spring. The water column is stable until the solar radiation penetrating through the ice begins to heat the water significantly. How the radiative heating and the resulting convection occur depends on the quality of the water via its optical properties.

Impurities are trapped in a lake ice sheet inside macro crystals at platelet boundaries and between macro crystals. The mechanisms are the following: (1) In congelation ice growth, the separation of the freezing water from dissolved substances and suspended matter is incomplete and pockets with liquid solution and sediment particles remain within the ice; (2) In particular floating particles and gas bubbles become captured rather than rejected by a growing ice sheet; (3) In turbulent supercooled water suspended particles serve as crystallization seeds for frazil ice or may become locked within frazil slush, later to become a part of the solid ice sheet; (4) Anchor ice, formed on the bottom of the water body from frazil ice in turbulent flow, may rise and by adhering to the ice cover bring bottom material into it; (5) Snow-ice formation brings impurities into the ice sheet from the snow cover and flooded lake water; and (6) Fallout from the atmosphere accumulates on the ice/snow cover. An ice sheet may contain pockets with liquid brine where the temperature corresponds to the freezing point of the brine, as is common in sea ice [11]. However, as the salinity of the lakes in Finland is very low ($\ll 10^{-3}$), the volume of the pockets containing liquid solution is very small and does not have any significant effect on the ice properties.

To map the quality and quantity of impurities in lake ice, a specific observation programme was performed in 1997–99 in Finland (Fig. 1; Tables 1 and 2). A pilot study preceded in 1996 [5]. The research lakes were Pääjärvi, Tuusulanjärvi, Vesijärvi, and Päijänne. The Porvoonjoki River was sampled for

Table 1. The studied lakes

Lake	Area, km^2	Depth, m		Eutrophication
		Mean	At site	
Pääjärvi	13	15.3	10	Meso-oligotrophic
Päijänne, southern basin	70	15.0	25	Oligotrophic
Vesijärvi (Lahti)	112	6.6	7	Eutrophic
Tuusulanjärvi	6	3.1	2	Hypereutrophic

Table 2. Samples 1996–99 (1–4 for lakes, 5–6 for the river); x – no data. Layer thicknesses and snow density are also given

No.	Site	Date	Ice, cm	Opaque top layer[1], cm	Snow	
					cm	g/cm^3
1/97	Pääjärvi	March 19, 1997	37	11	0	–
2/97	Päijänne	March 21, 1997	40	1	0	–
3/97	Vesijärvi (Lahti)	March 21, 1997	39	4	0	–
4/97	Tuusulanjärvi	March 23, 1997	32	2	0	–
5/97	Porvoonjoki (Pukkila)	March 21, 1997	21	14	4	x
6/97	Porvoonjoki (Porvoo)	March 21, 1997	28	13	0	–
1/98	Pääjärvi	March 27, 1998	52	10	5	0.33
2/98	Päijänne	March 27, 1998	63	8	5	0.22
3/98	Vesijärvi (Lahti)	March 27, 1998	55	7	5	0.26
4/98	Tuusulanjärvi	March 29, 1998	53	7	5	0.34
5/98	Porvoonjoki (Pukkila)	March 27, 1998	46	11	5	0.32
6/98	Porvoonjoki (Porvoo)	March 27, 1998	40	14	5	0.34
1/99	Pääjärvi	March 23, 1999	53	23	18	0.25
2/99	Päijänne	March 23, 1999	43	3	24	(0.5)[2]
3/99	Vesijärvi (Lahti)	March 23, 1999	42	3	31	(0.5)[2]
4/99	Tuusulanjärvi	March 28, 1999	59	23	5	0.55
5/99	Porvoonjoki (Pukkila)	March 23, 1999	45	31	5	0.32
6/99	Porvoonjoki (Porvoo)	March 23, 1999	53	36	5	0.37

[1] snow-ice in the lakes, snow-ice or frazil ice in the river;
[2] wet snow and lower 12 cm slush, 0.5 g/cm^3 is a rough average density

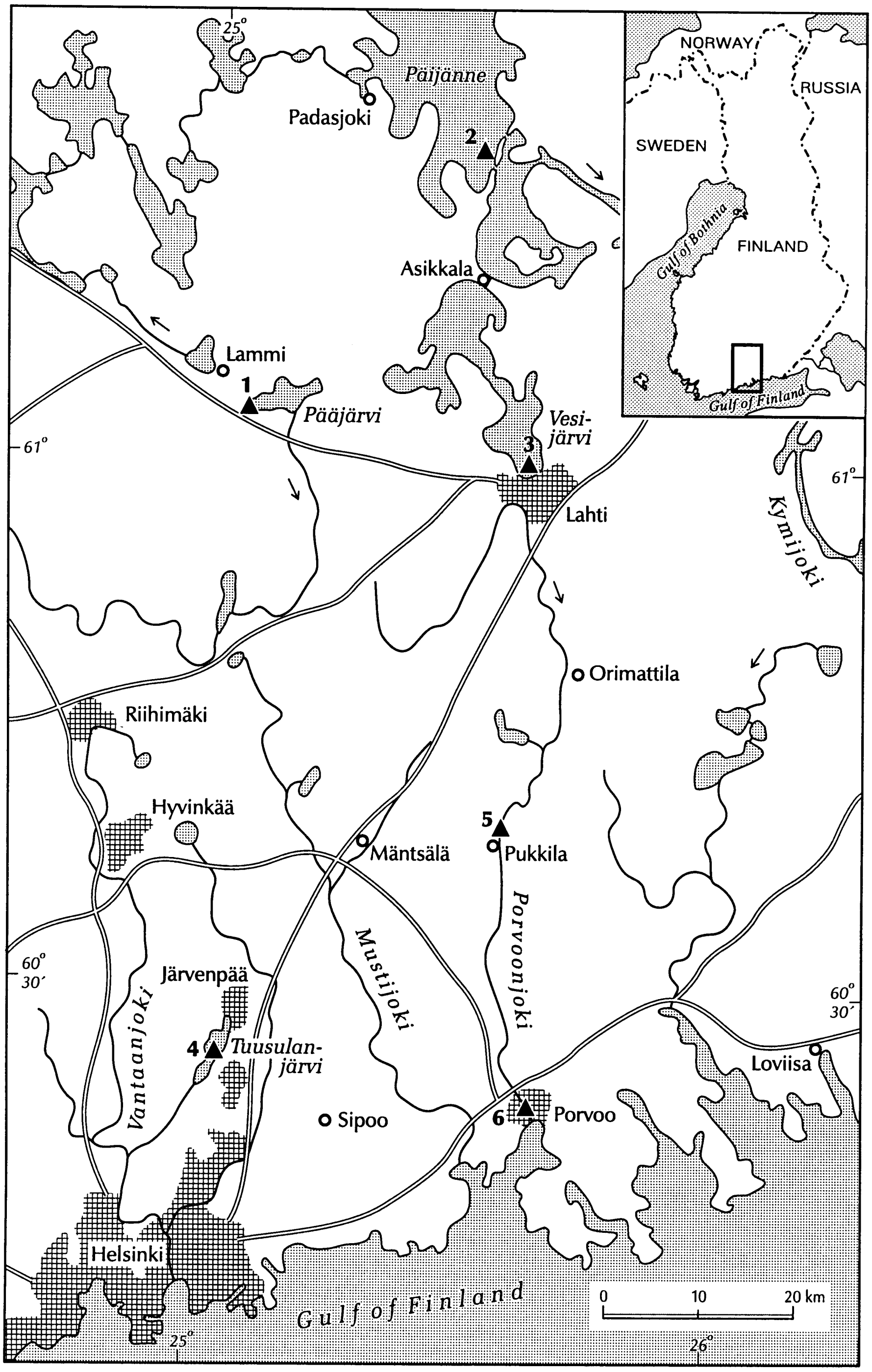

Fig. 1. Map showing the locations of the sampling sites.

comparison. This small river (length about 100 km) is located in southern Finland and flows into the Gulf of Finland. The sampling concerned two river sites, depth 2–3 m: No. 5 in Pukkila, upper river agricultural area, and No. 6 in Porvoo not far from the river mouth. For comparison with nearby sea ice, earlier results of Leppäranta et al. [5] from the Gulf of Finland were used.

The ice was sampled using a drill and an ice saw, the snow cover was carefully shovelled away from the ice. The structure and stratigraphy of the samples were recorded at the site. The snow samples were collected with plastic plates, cutting uniformly across the depth of the snow cover. Acid-washed 10-litre plastic buckets with plastic lids were used to transport and store these samples. A half-litre water sample was taken at the ice site. The samples were stored in a cold store room (+4 °C), the ice and water samples thus becoming melted. The meltwater volumes were 2–5 L.

The ice and snow meltwater and water samples were analysed according to the Finnish standards. The amount of sediments was determined by evaporation; the organic matter in the sediments was estimated by loss on ignition (LOI) after filtering (pore size 0.3–0.6 μm) according to [12, 13]. Electric conductivity and pH were measured from unfiltered samples according to [14, 15], and the amount of dissolved matter was measured from filtered sub-samples [12]. Concentrations of certain chemical elements (Al, Ca, Cd, Cu, Fe, K, Mg, Mn, NO_2N, NO_3-N, tot-N, Na, Ni, PO_4-P, tot-P, Pb, and Zn) were determined from ice- and snow-bound sediments. Metal concentrations were measured as acid soluble after wet digestion according to [16] using flame [16–20] and flameless [21, 22] atomic absorption with a Varian SpetrAA A10+ atomic absorption spectrophotometer and Varian GTA-95 graphite furnace. The concentrations of PO_4 and total phosphorus were measured photometrically by means of the molybdenum blue method with ascorbic acid reduction [23]. The sum of NO_2 and NO_3 and total nitrogen, after wet digestion [24], were measured according to [25]. The sulphate concentrations were measured according to [26]. All non-metal analyses were made with a DR Lange LS 500 UV/VIS spectrometer.

RESULTS

Ice thickness and structure

The ice sheet was stable fast ice in all sites. However, in 1998 ridge formation took place in the southern basin (Asikkalanselkä) of Lake Päijänne. Our sampling site was on the northern side of Pulkkilanharju esker. On the southern side of this esker, there was one floating ice ridge with sail height of 20–30 cm (Fig. 2). The ice sheet was likely weaker there because of water currents. Also on the shores of this basin ice pile-up was noted in many places. Ridging is very rare in the lakes in Finland because of limited fetch lengths. If more common, it would change the question of ice impurities by capturing water inside consolidating ridges and by bottom scouring.

Fig. 2. An ice ridge in Lake Päijänne at Pulkkilanharju esker, 21 March 1997.

The thermodynamic growth of lake ice thickness h is described in the first order by a modified Stefan's law (e.g. [27]):

$$h(t) = \lambda a \sqrt{S(t)}, \quad (1)$$

where λ is a reduction factor due to snow cover ($0.5 < \lambda < 1$), $a \approx$ 3.3 cm/(°C day)$^{1/2}$ is the growth factor for bare ice, and S is the sum of negative degree-days or the time integral of the below zero temperatures. The thickness of ice in the lakes was 32–40 cm in 1997, 52–63 cm in 1998, and 42–59 cm in 1999 (Table 2). The averages were 45–50 cm for the individual lakes and 37–56 cm for the individual years. The mean winter (December–February) temperature was –5.8 °C in 1997, –4.6 °C in 1998, and –6.7 °C in 1999, all a little above the normal (–7.4 °C), and the ice thickness was within one standard deviation from the average. In the normal case the freezing-degree-days sum to 700–800 °C day, which gives $\lambda \sim 2/3$.

The snow-ice thickness was 1–23 cm, 10% of the total ice thickness in 1997, 15% in 1998, and 10–40% in 1999. In 1999 the snow thickness on land was exceptionally large, and the snow-ice thickness was 23 cm in sites Nos. 1/99 and 4/99, but only 3 cm in sites Nos. 2/99 and 3/99 where the ice sheet could resist the snow load. In fact, due to the pressure in the water, there was a strong flooding event when the drill hole was made; as a result, in site No. 2/99 the water level became 12 cm above the ice surface.

The ice was bare in 1997, in 1998 the snow thickness was 5 cm in all sites, and there was 5–31 cm snow in 1999. The snow density was 0.22–0.34 g/cm^3 in

1998 while in 1999 very large values resulted as much of the snow was wet slush. River ice samples were thinner, 21–46 cm, and they showed a considerably larger portion of opaque top layer.

Dissolved matter, sediments, and pH

A property of ice, P_I, such as concentration of dissolved matter, is a combination of contributions from congelation ice (CI) and snow-ice, which further consists of snow (S) and lake water (W):

$$P_I = \gamma P_{CI} + (1 - \gamma)[\alpha P_S + (1 - \alpha)P_W], \quad (2)$$

where γ is the proportion of congelation ice and α is the proportion of snow in snow-ice. Here the former is observed and the latter is assumed equal to 0.5 according to [9]. In an average sense, $\gamma \approx 0.8$, and then an ice sample consists of 80% of congelation ice formed from the lake water with rejecting most impurities, 10% of snow, and 10% of lake water with its impurities captured. Thus snowfall and snow-ice formation add much impurities into the ice, and with the given γ and α applied for the present measurements, the contribution would be of the order of 50%. Dividing Eq. 2 with P_W and P_S, we obtain the concentration ratios

$$P_I/P_W = (1 - \gamma)(1 - \alpha) + \gamma P_{CI}/P_W + (1 - \gamma)\alpha P_S/P_W \quad (3a)$$

and

$$P_I/P_S = (1 - \gamma)\alpha + (1 - \alpha)(1 - \gamma)P_W/P_S + \gamma P_{CI}/P_S. \quad (3b)$$

The first terms in the right-hand side are ≈ 0.1, which is a lower limit of the ratios. The values on snow vary according to the atmospheric conditions during snowfall.

Table 3 shows the statistics for the bulk properties of the ice, snow, and water samples in the lakes. They include the electric conductivity, the concentration of dissolved matter, pH, and the concentration of sediments with the organic proportion specified. Variations exist between lakes. This is expected since they represent different lake types. There are also large interannual variations for each individual lake. The ice sediments were sometimes seen well by bare eyes as shown in Fig. 3 as an example.

The mean conductivity of the lake ice samples was 7–15 μS/cm, with the range of 4–28 μS/cm (at the reference temperature of 25 °C). The conductivity of snow averaged 9.5–28 μS/cm, being less than the conductivity of ice only in hypereutrophic Lake Tuusulanjärvi. The year 1998 gave the lowest values for the ice (4–7 μS/cm) and snow (10–12 μS/cm) in all lakes. The difference in the conductivity of ice and water was one order of magnitude, the water samples showing average conductivities of 79–208 μS/cm.

The concentration of dissolved matter behaved much like the conductivity. It was on average 14.3 mg/L in Lake Pääjärvi, 11.3 mg/L in Lake Päijänne,

Table 3. Bulk properties of the melted ice and snow samples and the water samples, average ± standard deviation; x – no data

Water body sample	Conductivity, µS/cm [25 °C]	Dissolved matter, mg/L	pH	Sediment content	
				mg/L	organic, %
Lake Pääjärvi					
Ice	13.0 ± 5.6	14.3 ± 5.5	6.7	2.1 ± 0.5	36
Snow	16.5 ± 7.8	15.0 ± 5.7	x	4.2 ± 3.4	38
Water	108.0 ± 5.2	64.0 ± 30.6	6.6	3.7 ± 4.2	40
Lake Päijänne					
Ice	7.7 ± 3.5	11.3 ± 4.0	6.6	2.1 ± 1.4	23
Snow	19.0 ± 8.5	20.0 ± 9.9	x	7.0 ± 5.9	50
Water	78.7 ± 5.5	31.3 ± 24.4	7.0	1.4 ± 0.6	49
Lake Vesijärvi					
Ice	7.0 ± 4.4	12.7 ± 5.5	6.6	2.0 ± 0.2	33
Snow	28.0 ± 22.6	23.5 ± 17.7	x	9.9 ± 9.5	54
Water	128.3 ± 3.2	52.3 ± 30.2	7.0	1.1 ± 0.4	50
Lake Tuusulanjärvi					
Ice	15.0 ± 11.8	17.3 ± 11.7	6.6	12.6 ± 5.0	24
Snow	9.5 ± 0.7	17.0 ± 15.6	x	11.6 ± 9.8	58
Water	208.3 ± 170.3	143.0 ± 152.2	6.8	11.5 ± 8.3	22
Porvoonjoki River					
Pukkila					
Ice	17.0 ± 11.8	24.0 ± 13.7	6.6	190.0 ± 291.1	31
Snow	28.0 ± 19.8	25.0 ± 17.0	x	64.2 ± 78.3	80
Water	239.0 ± 64.3	127.3 ± 80.1	6.9	16.0 ± 4.8	19
Porvoo					
Ice	19.0 ± 14.2	19.0 ± 14.9	6.6	24.5 ± 13.7	32
Snow	14.5 ± 0.8	15.5 ± 4.9	x	14.9 ± 7.8	56
Water	239.7 ± 74.3	135.0 ± 90.2	6.9	17.0 ± 5.2	19

12.7 mg/L in Lake Vesijärvi, and 17.3 mg/L in Lake Tuusulanjärvi. The minimum was 5 mg/L and the maximum was 28 mg/L, both in Lake Tuusulanjärvi. The average values in snow were a little higher except in Lake Tuusulanjärvi, being respectively, 15.0, 20.0, 23.5, and 17.0 mg/L for these lakes. The concentrations in water samples averaged 31–143 mg/L. For the water samples the concentration of dissolved matter (in mg/L) was about 0.5 times the conductivity (in µS/cm) as it should be but for ice and snow meltwater the ratios were larger, for ice always more than one. This fact reflects changes in the dissolved matter–suspended matter proportions in the melt–freeze cycles (e.g. [28]).

The ice was thus much cleaner than the water: the ratio of the average dissolved matter (DM) in ice to average dissolved matter in water was 0.22 in Lake Pääjärvi, 0.36 in Lake Päijänne, 0.24 in Lake Vesijärvi, and 0.12 in Lake Tuusulanjärvi. The coefficient of variation was 0.3–0.6 for ice, 0.3–0.9 for snow, and 0.5–1.0 for water. Considering Eq. 3a, the ratio DM_{CI}/DM_W is at most ~0.1 since the last term is very small. On the other hand, Eq. 3b tells that $DM_{CI} \sim DM_S$ to make the ratio DM_I/DM_S close to one.

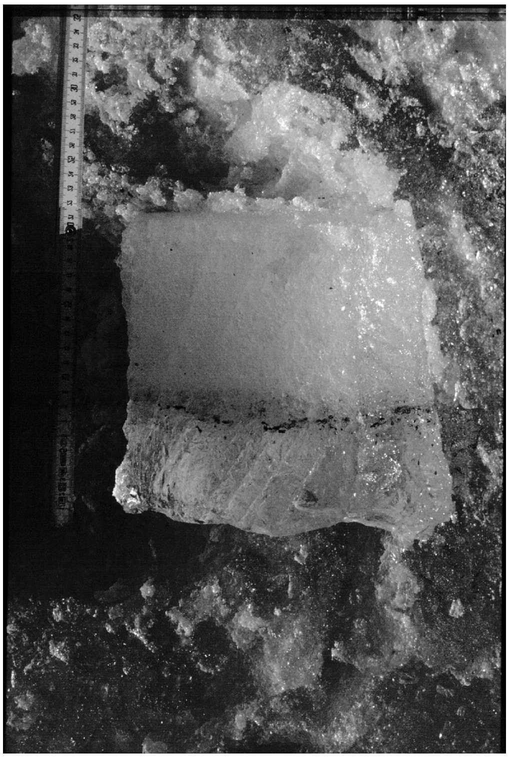

Fig. 3. Photograph of a thick section of the ice sheet at Pukkila, the Porvonjoki River, on 21 March 1997, showing a layer of dirt in the upper congelation ice.

Data for pH were obtained only in 1997 and 1999. The averages of ice and water pH were 6.6–7.0, ice pH being greater only in Lake Pääjärvi. In 1997 the values ranged from 5.9 to 6.8, and in 1999 the level was much higher, 6.7–7.3. The snow data are not given in Table 3 since snow data are only from 1999; then the snow pH was 0.2 units lower than the pH of water and ice. In 1976–81 snow samples (286) were studied in Finland and lower pH values were obtained: range 3.7–6.2 with a median of 4.6 [29].

The sediment content or suspended matter (SM) was roughly the same in ice and water. The average levels in ice were 2.1 mg/L in Lake Pääjärvi, 2.1 mg/L in Lake Päijänne, 2.0 mg/L in Lake Vesijärvi, and 12.6 mg/L in Lake Tuusulanjärvi. The minimum was 0.7 mg/L (Lake Pääjärvi 1997) and the maximum 20.8 mg/L (Lake Tuusulanjärvi 1998). The water samples showed averages of 3.7, 1.4, 1.1, and 11.5 mg/L. In the averages, the ratios of the sediments in ice to the suspended matter in water were in these lakes 0.57, 1.50, 1.82, and 1.10, respectively. The snow cover had higher sediment concentration levels in Lake Tuusulanjärvi where the level was 11.6 mg/L, just 1 mg/L lower than in ice. The coefficient of variation was 0.1–0.7 for ice, 0.8–1.0 for snow, and 0.4–1.0 for water. The mean proportion of organic matter in the ice sediments was 23–36%. In the snow the range was 38–

58% and in the water it was 22–50%. Considering Eqs. 3, we must have $SM_{CI} \sim SM_W$ and $SM_{CI} < SM_S$. Consequently, suspended matter is captured from the lake water much more efficiently than dissolved matter.

The river ice samples showed higher levels of impurities. The mean conductivity for the ice was 17.0 μS/cm in the upper river, and 19.0 μS/cm in Porvoo, and the mean dissolved matter contents were 24.0 and 19.0 mg/L, respectively. Both values are greater than in the lake data, and in 1999 the values were much higher than in the other years. The mean conductivity was about an order of magnitude larger in the river water. The ice–water ratio for the average dissolved matter content was 0.19 in the upper river and 0.14 in Porvoo. The pH was lower in the river ice samples than in the lake water samples in 1997, but in 1999 the opposite result was obtained. The sediment content was the highest in the ice. The maximum (526.0 mg/L) was registered in the upper river in 1997. The mean levels were much larger than in the lake data.

Chemical analyses

In lakes Pääjärvi, Vesijärvi, and Päijänne the metal concentration levels in the ice were around 100 μg/L for aluminium and iron, 30 μg/L for zinc, 6–9 μg/L for copper, and 1–7 μg/L for manganese and nickel (Table 4). The cadmium level was high (0.5 μg/L) in Lake Pääjärvi. Hypereutrophic Lake Tuusulanjärvi showed much higher levels for aluminium and iron (nearly 1000 μg/L) than the other lakes. River ice possessed much higher metal concentrations, as expected, but still comparable with the levels in the water. Exceptionally high values in ice relative to water were obtained for copper in both river sites.

The concentrations of metals in the ice relative to those in the water were within 0.5–2.0. Exceptions were cadmium (>5) and manganese (0.2) in Lake Pääjärvi, nickel (0.25) in Lake Vesijärvi, and manganese (0.2) in Lake Tuusulanjärvi. Comparing snow with ice, a low cadmium level was seen again in Lake Pääjärvi. In Lake Vesijärvi high aluminium, iron, manganese, and nickel concentrations were observed in the snow. In Lake Tuusulanjärvi the snow was poor in manganese. Snowfall is therefore a significant source for many metals. The maximum was found usually in the water except cadmium and copper for which the highest levels appeared in the ice.

The concentrations of heavy metals, except iron, in snow, ice, and lake water were quite small compared to concentrations in river and ground waters [30, 31]. Iron concentrations were high and variation between sampling sites was large. The reason for this can be redox conditions during winter and support from the catchment. Samples from Lake Tuusulanjärvi and Pukkila clearly show the effects of agriculture on lake and river water. Aluminium concentrations are also high in the samples from Lake Tuusulanjärvi and Pukkila. These values reflect the same source as for iron.

Except in Lake Tuusulanjärvi, nutrient levels in lake ice were usually the following (Table 5): total phosphorus 2 μg/L, total nitrogen 200 μg/L, sulphates 1 mg/L, chloride 1 mg/L, calcium 2 mg/L, magnesium 0.1–0.9 mg/L, potassium

Table 4. Average concentrations (μg/L) of metals from winters 1998–99

Water body	Al	Cd	Cu	Fe	Mn	Ni	Zn
Lake Pääjärvi							
Ice	102	0.5	6	149	4	7	28
Snow	216	<0.1	5	127	3	5	27
Water	99	<0.1	5	310	22	7	27
Lake Päijänne							
Ice	114	0.1	8	73	1	4	33
Snow	140	<0.1	5	110	3	4	25
Water	75	<0.1	6	87	2	3	56
Lake Vesijärvi							
Ice	94	<0.1	9	62	2	1	26
Snow	517	<0.1	5	303	7	6	36
Water	55	<0.1	5	40	2	4	55
Lake Tuusulanjärvi							
Ice	867	<0.1	5	965	9	4	29
Snow	416	<0.1	8	277	5	4	18
Water	2195	0.1	11	1710	53	9	50
Porvoonjoki River							
Pukkila							
Ice	1706	0.1	27	1278	21	5	32
Snow	1916	0.1	8	1676	39	10	21
Water	1680	0.1	7	1775	76	8	26
Porvoo							
Ice	1445	0.1	16	1094	17	6	32
Snow	626	0.2	6	707	9	6	26
Water	1795	<0.1	6	1545	63	12	48

0.5 mg/L, and sodium 1 mg/L. In hypereutrophic Lake Tuusulanjärvi the phosphorus and nitrogen levels were somewhat larger. The levels of nutrients in ice were much lower (by one order of magnitude) than in water. Exceptions were found only in Lake Päijänne, an oligotrophic water basin: the levels of phosphorus, calcium, magnesium, potassium, and sodium were about the same in the ice and the water. The concentrations in snow were usually close to the ice values. Nitrogen showed much higher snow levels in lakes Pääjärvi, Päijänne, and Vesijärvi, while the levels of phosphorus, sulphates, and magnesium in the snow were higher in Lake Vesijärvi.

According to different classifications [32, 33] the total phosphorus and total nitrogen values from Lake Pääjärvi and Lake Päijänne reflect mainly oligotrophy and mesotrophy. Some of the total nitrogen values are typical of eutrophy. The proportion of soluble NO_2 and NO_3 varies from 2% to 68% of the total nitrogen. Lakes Vesijärvi and Tuusulanjärvi and the Porvoonjoki River are clearly eutrophic. Some values from the Porvoonjoki can be regarded as indicating hypereutrophic conditions. Total nitrogen concentrations also reach values characteristic of hypereutrophic conditions. Sulphate and chloride concentrations are in the range typical of river waters [31].

Table 5. Nutrient concentrations in winter 1999

Water body	P		N		SO_4	Cl	Ca	Mg	K	Na
	$P\text{-}PO_4$	Tot	$N\text{-}NO_x$	Tot						
	µg/L				mg/L					
Lake Pääjärvi										
Ice	2	3	95	260	1.5	0.9	2.5	0.2	0.3	0.4
Snow	<2	3	592	978	2.8	0.9	1.6	0.2	0.3	0.5
Water	5	14	867	1257	18.0	7.5	8.6	2.7	2.4	4.2
Lake Päijänne										
Ice	<2	2	11	102	<1	0.3	3.2	0.9	1.0	3.8
Snow	<2	4	390	590	2.4	1.8	1.8	0.3	0.4	1.0
Water	<2	4	225	487	9.4	6.3	2.6	0.7	0.9	3.1
Lake Vesijärvi										
Ice	<2	<2	<5	204	<1	0.4	1.2	0.1	0.3	0.3
Snow	5	10	232	755	4.5	3.0	2.4	0.6	0.8	1.2
Water	22	28	185	567	14.0	9.5	10.4	3.7	3.1	6.1
Lake Tuusulanjärvi										
Ice	8	18	213	487	2.1	1.7	2.4	0.5	0.5	0.8
Snow	5	6	130	318	<1	0.4	1.3	0.1	0.3	0.3
Water	40	85	3216	4799	39.0	31.0	16.9	10.0	4.8	14.4
Porvoonjoki River										
Pukkila										
Ice	40	61	555	687	2.5	1.7	2.1	0.6	1.3	1.1
Snow	14	24	853	1394	4.4	2.4	3.6	1.0	0.7	1.3
Water	82	121	4870	6068	28.0	21.0	15.7	6.0	9.3	20.5
Porvoo										
Ice	38	64	664	848	2.7	2.4	1.8	0.6	0.8	1.3
Snow	5	16	431	933	1.1	1.0	1.2	0.2	0.4	0.6
Water	74	118	3920	4910	29.0	23.0	14.7	7.0	7.7	21.3

Vertical stratification

Information on the vertical stratification is available for lakes Pääjärvi and Tuusulanjärvi from an optics field campaign on 26–27 March 1996. The measurements were made of conductivity, concentration of yellow substance, chlorophyll *a*, and sediments for 10-cm vertical resolution, the volume of each sample being about one litre. Yellow substance, a concept used in optics of natural water bodies, consists of dissolved organic matter, which absorbs light in short wavelengths. The concentration of yellow substance was obtained from light beam attenuation measurements, that of sediments by filtering (pore size 0.45 µm), and of chlorophyll *a* by the filter pad technique.

The vertical stratification data are shown in Fig. 4. The profiles are quite different. Lake Tuusulanjärvi shows higher levels for all three columns. Pääjärvi ice is poor in dissolved matter except for the top layer, which was snow-ice. Chlorophyll *a* level is 6 mg/m^3 and then decreases with depth in Tuusulanjärvi. In Pääjärvi the value is very low. The ratio of the concentrations in ice and water

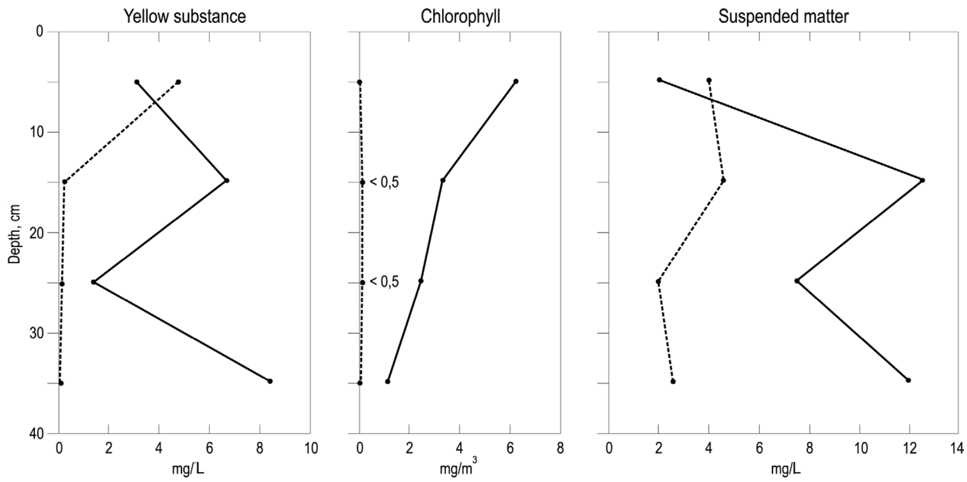

Fig. 4. The vertical structure of the yellow substance, chlorophyll *a*, and suspended matter for lakes Tuusulanjärvi, 26 March 1996 (solid line), and Pääjärvi, 27 March 1996 (dashed line).

was in round numbers 0.1 for the yellow substance and 0.5 for the sediment content; for the chlorophyll *a* the ratio was 2.5 in Tuusulanjärvi and below 0.16 in Pääjärvi. Ignoring the snow-ice layer, the yellow substance ratio goes down to 0.01 in Pääjärvi but does not change much in hypereutrophic Lake Tuusulanjärvi. The levels in the water were: yellow substance 41.7 and 26.0 mg/L, chlorophyll *a* 1.2 and 3.1 mg/m^3, and suspended matter 11.9 and 13.0 mg/L in lakes Tuusulanjärvi and Pääjärvi, respectively.

From Lake Pääjärvi another dataset is available for winter 1999. Five layers were sampled separately: new snow, old snow, snow-ice, congelation ice, and water (Table 6). The results confirmed the deductions from the bulk data. The highest levels occurred usually in water; exceptions were copper and zinc in snow and nickel in congelation ice. Except for copper the lowest concentrations occurred in snow and ice, and about equally often in both.

In general, the results for the snow are close to those for the ice. This is likely due to the major role of atmospheric fallout as the source of impurities. The fallout contributes to the ice when the ice is bare and via the formation of snow-ice. In our earlier study in 1996, pH values below 4 were observed in ice and snow but the minimum was 5.9 in the present work. However, in general snowfall brings acid deposits down from the atmosphere and these deposits accumulate into the snow layer during the whole ice season. In 1976–81 the snow samples (286) studied in Finland had a pH range of 3.7–6.2 with a median of 4.6 [29].

Table 6. Results for vertical stratification in Lake Pääjärvi, 1999

Parameter	New snow	Old snow	Snow-ice	Congelation ice	Water
Conductivity, μS/cm	12.7	25.7	23.6	7.8	105
Dissolved matter, mg/L	20	19	16	18	32
Sediments, mg/L	1.2	2.1	3.3	1.6	3.6
pH	6.99	6.59	7.17	7.32	6.97
Aluminium, μg/L	62	51	56	41	98
Cadmium, μg/L	<0.1	<0.1	<0.1	<0.1	<0.1
Copper, μg/L	4.2	6.9	5.5	5.0	3.4
Iron, μg/L	32	46	56	41	383
Manganese, μg/L	0.3	4.9	5.1	0.4	21.6
Nickel, μg/L	2	3	5	9	7
Zinc, μg/L	46.2	6.4	26.3	29.9	16.8
Calcium, mg/L	1.8	2.2	5.9	1.8	8.5
Magnesium, mg/L	<0.1	0.5	0.5	<0.1	2.6
Potassium, mg/L	0.1	0.4	0.4	0.1	2.2
Sodium, mg/L	0.2	0.8	0.7	0.2	4.1
PO_4-phosphorus, μg/L	<2	<2	3	<2	5
Total phosphorus, μg/L	<2	4	5	<2	14
NO_3- & NO_2-nitrogen, μg/L	485	699	176	13	867
Total nitrogen, μg/L	933	1023	407	113	1257
Sulphate, mg/L	1.2	4.4	2.6	<1	18
Chloride, mg/L	0.3	1.4	1.3	0.4	7.5

CONCLUSIONS

Ice, snow, and water samples were taken from four Finnish lakes in winters 1997–99 for determining the quality and quantity of impurities (for ice and snow from the meltwater). The data include pH, electric conductivity, and dissolved matter concentration, and for the suspended matter within the ice include the total mass, organic proportion, and concentrations of chemical elements. One river was examined for comparisons.

The average concentration of dissolved matter was 11–17 mg/L in ice, 15–23 mg/L in snow, and 31–143 mg/L in water, i.e. $DM_I \sim DM_S << DM_W$. The sediment content was in these media, respectively, 2–12 mg/L, 4–11 mg/L, and 1–11 mg/L, i.e. $SM_I \sim SM_S \sim SM_W$; in cleaner waters the level was the highest in the snow. The organic proportion was 5–85% in the sediments. In general, the results for the snow are close to those in the ice, which is likely due to the major role of atmospheric fallout as the source of impurities. The fallout contributes to the ice when the ice is bare and via the formation of snow-ice. The river ice sites showed sediment content higher by one order of magnitude than in lake ice.

The concentration of dissolved matter in the lake ice amounted to the fraction of 0.1–0.4 of that in the lake water. The level is close to that found for the brackish waters on the coast of the Gulf of Finland [5]. But the level should be still much less if the dissolved matter originated from the lake water in congelation ice growth (e.g., [11]). This suggests that the dissolved impurities observed were mainly from the snow-ice growth and atmospheric fallout. The observed levels in the snow cover and the more detailed vertical stratification also support this suggestion.

Metal concentrations in the ice were usually around 100 μg/L for aluminium and iron; 30 μg/L for zinc; 1–10 μg/L for copper, manganese, and nickel; and below 0.1 μg/L for cadmium. Exceptions were high levels of aluminium and iron in Lake Tuusulanjärvi and a high level of cadmium in Lake Pääjärvi. The concentrations in the ice relative to those in the water were within 0.5–2.0. Snowfall is a significant source for many metals. The maximum was usually found in the water except for cadmium and copper for which the highest levels appeared in the ice. Nutrient levels in the ice were usually the following: total phosphorus 2 μg/L, total nitrogen 200 μg/L, sulphates 1 mg/L, chloride 1 mg/L, calcium 2 mg/L, magnesium 0.1–0.9 mg/L, potassium 0.5 mg/L, and sodium 1 mg/L. The levels were much lower (by one order of magnitude) than in the water. Nitrogen showed much higher levels in the snow in lakes Pääjärvi, Päijänne, and Vesijärvi; also phosphorus, sulphates, and magnesium levels were high in the snow in Lake Vesijärvi.

The storage and later release of sediments may become an important ecological factor especially as the load of harmful substances to natural water bodies increases. The accumulation takes place during the whole ice season (3–7 months in Finnish lakes), while the load is released to lake water within one month. Part of the ice sediments sinks contributing to the bottom sediments, while the rest remains in the surface layer. The effect of the meltwater load depends on the stratification of the water column. Under lake ice there is normally a thin (one metre or so) stable layer, and then the meltwater load may be heavy.

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Soome järvede jääs esinevate lisandite vaatlus

Matti Leppäranta, Matti Tikkanen ja Juhani Virkanen

Analüüsiti jääs ja lumes (sulavees) ning vees leiduvaid lisandeid. Proovid olid kogutud neljast järvest kolme aasta jooksul. Jää paksus oli 30–60 cm. Jääs oli keskmine lahustunud aine sisaldus 11–17 mg/l ja lumes 15–23 mg/l. Nimetatud väärtused moodustasid 10–40% lahustunud aine kontsentratsioonist vees. Tahke aine hulk oli kõigis keskkondades 2–12 mg/l. Metallilistest elementidest oli jääs keskmiselt 100 μg/l Al ja Fe, 30 μg/l Zn, 1–10 μg/l Cu, Mn ja Ni, alla 0,1 μg/l Cd. Nende sisaldus jääs oli 0,5–2,0-kordne võrreldes veega. Lumesadu kandis keskkonda ohtralt mitmesuguseid metalle. Toitaineid oli jääs järgmiselt: üld-P 2 μg/l, üld-N 200 μg/l, SO_4, Na ja Cl 1 mg/l, Ca 2 mg/l, Mg ja K 0,5 mg/l. Vees oli nimetatud elemente suurusjärgu võrra rohkem. Jõejääst võeti võrdlusproovid kahest kohast ja nendes oli tahke aine sisaldus ühe suurusjärgu võrra suurem kui järvejääs.