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Environmental factors related to water level regulation — a comparative study in northern Finland

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The environmental conditions of the littoral zone were studied in the regulated Lake Ontojärvi and the unregulated Lake Lentua in northern Finland. The general aims of the study were to analyse the environmental factors related to water level regulation in the littoral zone and to produce information for assessing the effects of hydroelectric development in northern lakes. The study was basically carried out by comparing the littoral environments of the two study lakes. The most visible effects of water level regulation were related to the raised water level, which yielded erosion of sandy shores at the beginning of the regulation. Another effect of lake regulation was the altered fluctuation of the water level, which led to bottom instability and increased the size of the frozen and ice penetration zones. The effect of ice penetration was also easy to recognize on the shores of Lake Ontojärvi, where the surface sediment was frozen to a greater depth and across wider areas than in Lake Lentua. Below the freezing zone, the ice just pressed down on the sediment. The shores of Lake Ontojärvi were steeper than those of Lake Lentua, what affected the distribution of bottom types, with sandy bottoms being more common in Lake Lentua than in Lake Ontojärvi. The factors related to site exposure included effective fetch and the shape of the shoreline. The sedimentation level correlated only with the slope and was not predicted by the fetch or shape. The vertical reduction of light was estimated on the basis of water colour. The main environmental factors from the two lakes were used in a discriminant analysis to predict the bottom type distribution of the littoral (r^2 = 0.41).

Introduction

About 10% (33 522 km^2) of the total area of Finland is covered by lakes, and the water levels in over one-third of this lake area (11 900 km^2, including nearly 220 lakes of > 1 km^2) are regulated (Alasaarela *et al.* 1989a). The main purpose of lake regulation in northern Finland is production

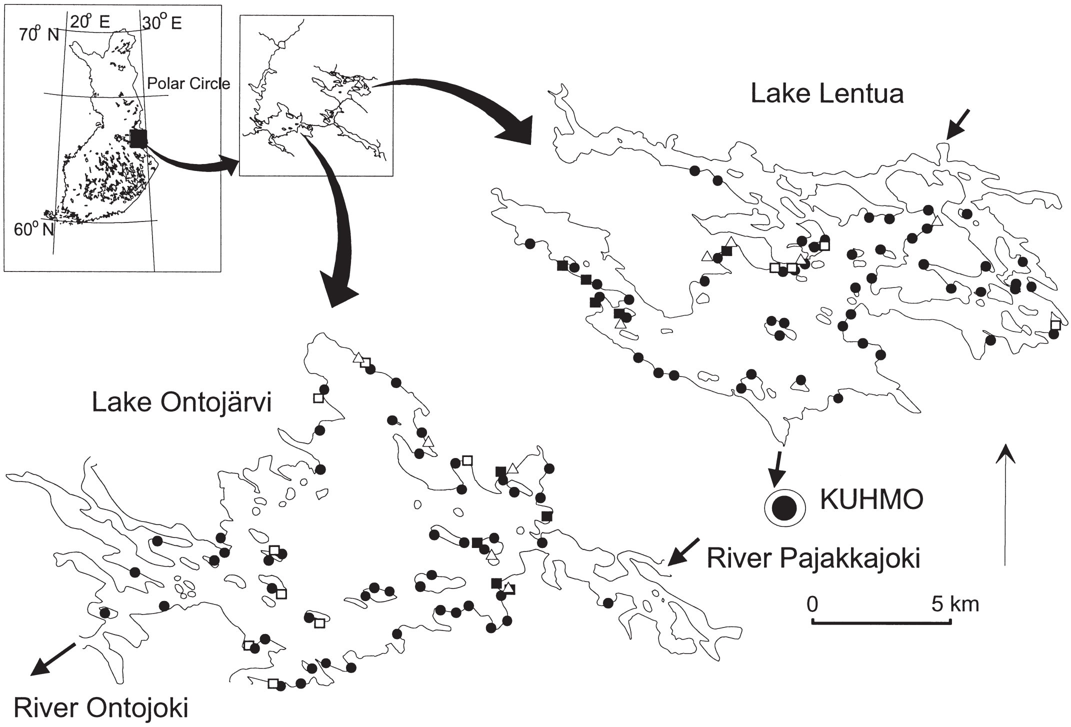

Fig. 1. Geographic location of Lake Ontojärvi and Lake Lentua in Finland. The transects (O1–52, L1–53, Appendix) have been marked with filled dots, the frost-tube measurement areas (Oi1–6, Li1–5) with filled squares, the other frost transects with open squares, and the bottom stability measurement points with open triangles.

of hydro-electric power. The lakes in northern Finland are generally more intensively regulated than those further south. In a typical regulation scheme, the water level is raised by 0.5–3.5 m in summer and lowered by 2–7 m in winter.

At the beginning of lake level regulation, the littoral undergoes considerable changes, especially if the water level is raised to increase the storage capacity of the lake (Sundborg 1977, Nilsson 1981, Newbury and McCullough 1984, Rørslett 1988, Alasaarela *et al.* 1989b). This causes major geomorphologic changes, including breakdown of humic substances and erosion of minerogenic matter. In most cases, the water level is lowered during winter, when the price of electricity is highest. Ice extends down to the bottom, causing the sediment to freeze and erosive scouring to take place (Nilsson 1981, Erixon 1981, Rørslett 1985). During early spring the water level is low and the spring flood is, therefore, much lower than average, and shifts towards midsummer (Alasaarela *et al.* 1989a). The effects of water level regulation are also clearly related to water quality; lakes with clear water are much more resistant against fluctuating water level due to the wider productive zone as compared to lakes with humic water (Rørslett 1988, Palomäki 1993). Despite the wide range of research on regulated lakes, there are only a few studies where the effects of water level regulation on the littoral were evaluated in details using statistical models (Rørslett 1988, Palomäki 1993).

The primary aim of this study was to identify and describe environmental factors affecting the littoral zone of a lake under the regulated water level. A second and more general goal was to provide information for assessing the effects of hydroelectric development in northern lakes. The study lakes were selected to obtain information applicable to northern Finland. Since there are no data available on the state of the lakes prior to regulation, the project was largely accomplished by comparing the regulated Lake Ontojärvi to Lake Lentua, which is in a natural state (hereafter RLO and NLL, respectively).

Study lakes

NLL is the largest non-regulated lake in the river Oulujoki watercourse (Fig. 1). RLO has been regulated for hydroelectric purposes since 1951 with a maximal range of 4.4 m (Table 1). At the beginning of regulation, the summer water level was raised by over one metre. The largest inlet is the river Pajakkajoki (F = 3 495 km^2) running from Lakes Lentua and Lammasjärvi (Fig. 1). The outlet, the river Ontojoki, is dammed by a hydroelectric power station.

The drainage basins of both lakes consist mainly of moraines, peatlands, sand and esker. From the geological viewpoint, NLL is a lake on gneiss-granite bedrock, while RLO is situated in the middle of a schistous quartz-feldspar area (for details, see Alasaarela *et al*. 1989a).

The long-term (1931–60) mean annual temperature measured at the airport of Kajaani, 80 km W of Kuhmo, is + 1.9 °C. The first year (1984) of the three-year study period (1984–1986) was

Table 1. Main hydrological and geomorphological features of the research lakes (Alasaarela *et al*. 1989a). The water quality parameters are presented as mean summertime values (± *S.D.*) (Jun.–Aug.) in the surface water (1–5 m) in 1984–86. * = number of observations of chl. a. [1)]Laasanen (1982)

	Lake Ontojärvi	Lake Lentua
Surface area, km^2	101.9 (NW 73.5, HW 114.8)	90
Mean depth, m	6.4	7.6
Water volume, mill.m^3	602	612
Drainage area, km^2	5015	2065
Mean discharge, m^3 s^{-1}	57	24
Water level 1960–79		
In natural state	NW 156.38	NW 167.12
(m a.s.l)	MNW 156.81	
	MW 157.33	MW 167.61
	MHW 158.30	
	HW 159.45	HW 168.78
Regulated	NW 155.00	
(m a.s.l)	MW 157.76	
	HW 159.40	
Duration of ice-free		
period 1960–79[1)], d	175	178
Ice-on		
χ 1960–79[1)]	11 Nov.	16 Nov.
1984	23 Nov.	22 Nov.
1985	15 Nov.	19 Nov.
1986	3 Dec.	6 Dec.
Ice-out		
χ 1960–79[1)]	20 May.	22 May
1984	12 May	15 May
1985	1 Jun.	1 Jun.
1986	18 May	18 May
Length of the shoreline, km	152	136
Sandy shores	13 %	14 %
Rocky shores	7 %	40 %
Moraine shores	67.5 %	36 %
Peaty shores	12.5 %	10 %
Water quality		
number of obs.	29	44
pH	6.5 (0.1)	6.7 (0.3)
Colour, mg Pt l^{-1}	65 (19)	54 (6)
Tot N, μg l^{-1}	345 (149)	359 (96)
Tot P, μg l^{-1}	15 (4)	15 (11)
Chl. a, μg l^{-1}	5.5 (1.9) 15*	3.6 (1.3) 13*

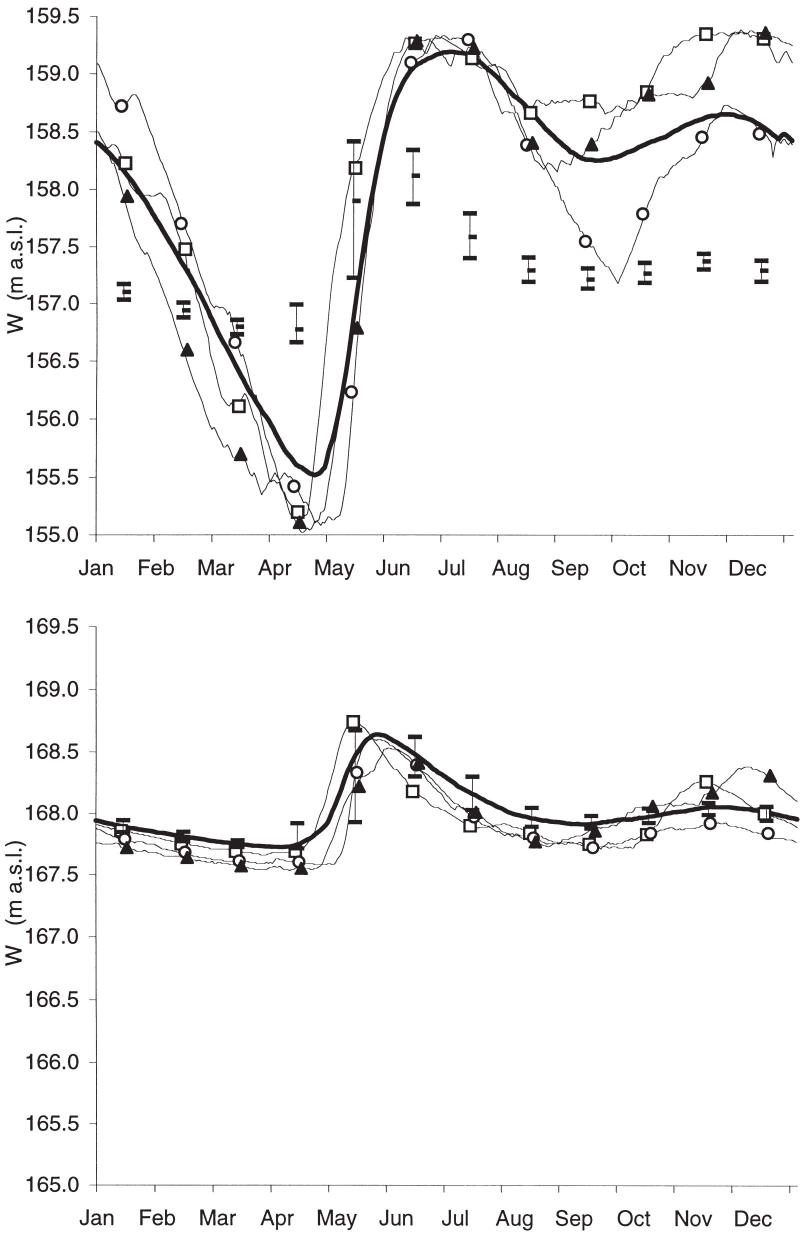

Fig. 2. Water level fluctuation in RLO (upper panel) and in NLL (lower panel). The thin lines represents daily levels (1984 = open squares, 1985 = open dots, 1986 = filled triangles) and the thick line the observed mean value during 1960-86. The HiLo-lines in the upper panels represent the recalculated (in natural state) water level (MHW, MW, MNW) during 1960–86 in RLO.

slightly warmer (annual mean, + 2.6 °C) than the two subsequent years (– 0.7 °C in 1985, – 1.0 °C in 1986). The calculated frost sum was –1 750 °C during the winter 1984–85 and –1 550 °C during the winter 1985–86. The mean annual precipitation (1931–60) measured at the Kuhmo meteorological station is 556 mm. All the study years were rainier than usual (1984: 639 mm, 1985: 570 mm, 1986: 682 mm). The maximum thickness of snow was 65 cm in 1985 and 75 cm in 1986.

The two study lakes are meso-oligotrophic, but RLO has more nutrient-rich water than NLL, due to the higher phosphorus contents of the incoming water from Lake Lammasjärvi (Table 1). Also, the colour of the water is darker and the biomass of phytoplankton is higher in RLO than in NLL.

Methods

Most of the field work was carried out in 1984–89 (Alasaarela *et al.* 1989a). Preliminary results were published earlier in Hellsten *et al.* (1989). The geomorphology of the shores was investigated by field work. The shores were divided into four basic soil types: moraine, sandy, peaty and rocky shores. On the basis of the distribution of the different shore types and exposure, 52 transects were selected from RLO and 53 from NLL (Fig. 1, Appendix). The transects were run from the highest water level to a depth of 2.5 m. The entire material consisted of 6 303 quadrats (1 m^2) situated at one or two-metre intervals, depending on the homogeneity of the bottom. The bottom substrate was visually classified into six classes: peat, stone, gravel, sand, muddy sand and mud.

The water levels were recorded daily during the study period from an official water gauge (Fig. 2). The median water level of the ice-free period (W_{om}) was used as a datum level. The relative water level (z, metres) was calculated from W_{om}, using the following formula:

$$z = W - W_{om} \quad (1)$$

where W is the transient water level in metres above sea level.

All depths (D) presented in this study are related to the relative water level (z) according to:

$$D = \begin{cases} |z| & \text{when } z < 0 \\ 0 & \text{when } z \geq 0 \end{cases} \quad (2)$$

The thickness of the frost layer was measured with double plastic tubes. The inner tube was filled with methylene blue liquid, the colour of which, changes from blue to white upon freezing. The tubes were inserted through the ice cover into the sediment at different levels (0.5 m intervals) along 5–6 different transects in both research lakes (four transects in RLO in 1984–85). The number of measuring tubes was 40–44 in RLO, and 18–21 in NLL during the winters 1984–85 and 1985–86, respectively. The state of the surface sediment was checked through holes drilled in the ice cover in March 1985 and 1986. This procedure was carried out at 13 sites in RLO and 9 sites in NLL during both research years. The results may be partly misleading due to the temperature-conductive properties of the tubes, which may overestimate the thickness of the frozen sediment.

Bottom stability was measured using sediment samplers, which were metal plates (780 cm^2) with a rough painted surface. The plates were fixed to the bottom with iron rods in ten different shore areas during the summers 1984 and 1985 (Fig. 1). The trapped sediment was collected with a suction sampler operated by scuba divers. Ignition loss and total amount (dry weight) of material were measured in a laboratory. The sedimentation depth (D_s) was determined as the boundary at which bottom quality changes from sand or stone to muddy sand or mud.

The slope (S) of the littoral was calculated as an inclination (%) between the depths of 0–1 metres (S_1) and 1–2 metres (S_2) or as a mean value (S_m) of S_1 and S_2. The continuous slope (S_c) value was calculated as an inclination (%) between adjacent quadrats along a given transect.

Exposure was assessed by the effective fetch (F_e), which refers to the free water surface over which wind may act upon waves (Håkansson and Jansson 1983). The distance (x) in kilometres from the measurement point to the nearest land or to an island was measured for every deviation angle (γ_i), where $\gamma_i = \pm 6°, \pm 12°,...,\pm 42°$, and the effective fetch (F_e) was calculated according to Håkansson and Jansson (1983);

$$F_e = \left(\frac{\sum x_i \cos \gamma_i}{\sum \cos \gamma_i} \right) \times ' s \quad (3)$$

where: cos γ_i = 13.5, a constant, 's = scale constant (e.g. 0.2 for a map scale of 1 : 20 000).

The shape (C) of the shoreline was measured on a map (scale 1 : 20 000) as an angle by setting the centre of a circle with a 2.5 cm or 5 cm radius on the shore line (Palomäki 1992). These radii represent 0.5 and 1 kilometer in the field. The opening angle of the shore was measured as degrees from the perimeter of the circle. Therefore, bays have values less than 180° and capes more than 180°. The shape (C) was presented as degrees using either a 0.5 km ($C_{0.5}$) or 1 km (C_1) circle.

Erosion of the bottom sediment was calculated with the SMB method presented originally in the Shore Protection Manual by the U.S. Army Coastal

Eng. (1977). In my study, the SMB method was applied using the same equations as in Lake Pyhäjärvi in southern Finland (Huttula 1994), with the wind speed, fetch and water depth as input values. The equations give the significant wave height, period and length. The erosion of resuspended material was calculated as proposed by Virtanen *et al.* (1988) and Huttula (1992), with a wind speed of 10 m s^{-1}. The relative erosion rate (R) of the bottom sediment yielded estimates (g m^{-2} d^{-1}) of sediment sediment erosion in the different quadrats. R values calculated for a depth of 0.01 m were used for all quadrats situated above W_{om} ($D = 0$) along a given transect.

The SPSS version of discriminant analysis was used to estimate the relative importance of five factors (water level duration d_w, continuous slope S_c, duration of frozen zone d_f, duration of ice pressure zone d_i and relative erosion rate R) affecting the formation of bottom quality classes. Only the factors with continuous non-classified values in every quadrat were chosen. The method of Moss *et al.* (1987) was used to predict the probability of the presence of each bottom class at the chosen test site. The set of f discriminant scores was calculated by using the discriminant function coefficients and environmental variables for that site. Further, the Euclidean distance from the scores of the sites to the mean score of each bottom class was calculated using the following formula:

$$x_j^2 = \sum_{i=1}^{f} \left(x_i - m_{i,j}\right) \quad (4)$$

where, X_j^2 = square of the distance from the site to class j, and $m_{i,j}$ = mean of function i for class j.

The probability that the site would be a member of each class is calculated as follows (Moss *et al.* 1987):

$$p_j = \frac{q_i}{\sum_{j=1}^{15} q_i} \quad (5)$$

where, $q_i = n_j \times \exp(-d_j^2/2)$ and n_j = number of members in bottom class j.

The estimation of the underwater light climate was based on the penetration of photosynthetically available radiation (PAR) calculated for some lakes of Central Finland (Eloranta 1978). Water colour/red light extinction relationships were calculated from the original measurements of light penetration presented by Eloranta (1978);

$$E_r = 0.25A^{0.42}, \text{ (with } r = -0.82, n = 30) \quad (6)$$

where: E_r = extinction coefficient of red light, A = water colour (mg Pt l^{-1}).

In this study, 4.5% of incident red light was used as an indicator of the lowest limit of productive littoral (Eloranta and Marja-aho 1982). The depth of the zone (D_r) reached by 4.5 % of incident red light (627 nm) can be calculated from the Lambert-Beer law;

$$D_r = \frac{-\ln(0.045)}{E_r} \quad (7)$$

The light zones of the study lakes were assessed according to the Lambert-Beer law;

$$L_D = L_0 \exp(-E_r D) \quad (8)$$

where: L_D = intensity of red light at a depth of D, L_0 = intensity of red light just below the surface.

Results

Water level fluctuation

Compared with its natural state, the summer water level of RLO is 1 m higher and the winter water level 1.5 m lower, i.e. almost 3 m below the summer mean (Fig. 2). The water fluctuates rather widely during the growing season and the flood peak occurs in the middle of July. NLL is a typical Finnish lake with regard to water level fluctuations. The water level reaches its minimum during the early spring, and the flood peak occurs at the end of May, but the summer fluctuation is quite small.

The years 1984 and 1986 were warmer than usual, and the spring flood occurred quite early in RLO (Fig. 2). During the autumn, the water level was higher than the average. The winter 1985 was significantly colder than normal with a late spring flood. Similar fluctuation was also observed in NLL. During the summer 1985, the water level of RLO was unexpectedly lowered by one metre due to repairs of the hydropower plant.

The shapes of the water level duration (d_w) curves and the vertical extent of water level fluctuation zones

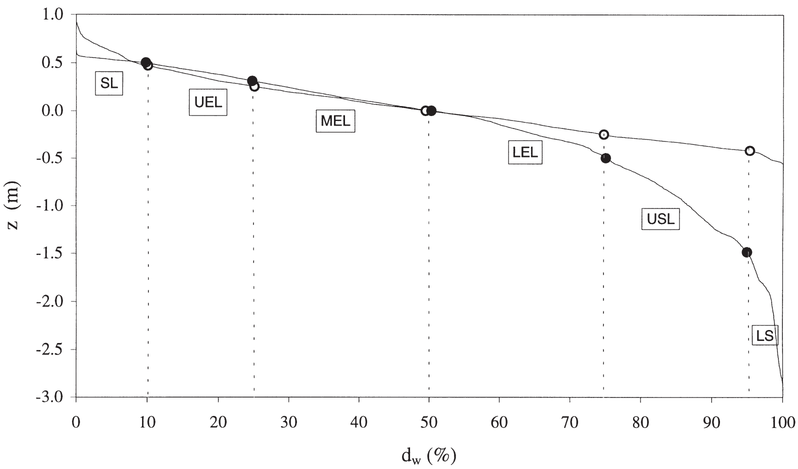

Fig. 3. Water level duration (d_w) curves in RLO (filled dots) and in NLL (open dots) during the open water period (1960–83). The water level fluctuation zones are outlined with dashed lines, SL = supralittoral, UEL = upper eulittoral, MEL = middle eulittoral, LEL = lower eulittoral, USL = upper sublittoral, LSL = lower sublittoral.

for the open-water period are different in RLO compared to NLL (Fig. 3). NLL had a sharp flood peak instead of the low peak which occurred in RLO. The supralittoral, which lies between the highest water level and 10 % duration level ($0 < d_w \leq 10$), reached a vertical extent of 0.12 m in RLO, whereas in NLL it is as wide as 0.44 m. The upper eulittoral ($10 < d_w \leq 25$) and the middle eulittoral ($25 < d_w \leq 50$) reached quite similar vertical extent in both lakes. The lower eulittoral ($50 < d_w \leq 75$) and especially the upper sublittoral ($75 < d_w \leq 95$) are much wider in RLO compared to NLL. The lower sublittoral ($d_w > 95$) consists of a vertical extent of 1.37 m in RLO and only 0.14 m in NLL, until the duration of 100 % or permanent submersion is reached. The median water level ($d_w = 50$ %) of the open-water period (W_{om}) is 158.83 m in RLO and 168.10 m in NLL.

Ice pressure on the littoral

As a consequence of the descending water level in winter, the ice presses against the bottom sediment (Fig. 4). This ice pressure zone can be divided into two subzones: the frozen ice pressure zone, where the surface of the bottom sediment is frozen, and the non-frozen ice pressure zone, where the descending ice cover just causes mechanical stress and hardening of the bottom without freezing of the surface sediment. In RLO, the frozen zone reached a depth of 1.3–2 m and the non-frozen zone a depth of 4 m (Fig. 4A). In NLL, only the uppermost part of the littoral was frozen, and the non-frozen zone also remained quite small (Fig. 4B).

The thickness of the frozen sediment measured by frost tubes was quite similar in the shallow part of the littoral of both lakes, although the differences were clearer in the littoral deeper than 0.5 m (Fig. 5). Frost depth attained its maximum values on minerogenic shores in both lakes, being 0.6 m and almost 0.8 m in RLO and in NLL, respectively. On the other hand, peat bottoms can resist frost most effectively; the thickness of frost was small, and soil frost was limited to the uppermost part of the littoral.

The zone of frozen sediment was the largest on sandy shores, but the difference compared to moraine shores was small (Table 2). The smallest values were observed on peaty shores. The freezing of the surface sediment reached two- to threefold depths in RLO as compared to NLL. The difference between years was also clear in RLO, because the low water level of the autumn 1985 caused extensive sediment freezing during the following winter. The winter 1985–86 was colder with a thick snow cover as compared to the winter 1984–85 (see Description of the study area), but the ice thicknesses were nearly identical.

The freezing of the bottom sediment begins when the insulating water layer is replaced by descending ice. The dates when the ice cover reached the deepest limit of the observed frozen zone are presented in Table 2. During both winters, frost reached that level between 4 and 9 of February in RLO, while in NLL the date varied between 11 and 31 January. In general, the lowest level of the frozen ice pressure zone (D_f) can be estimated using the following formula:

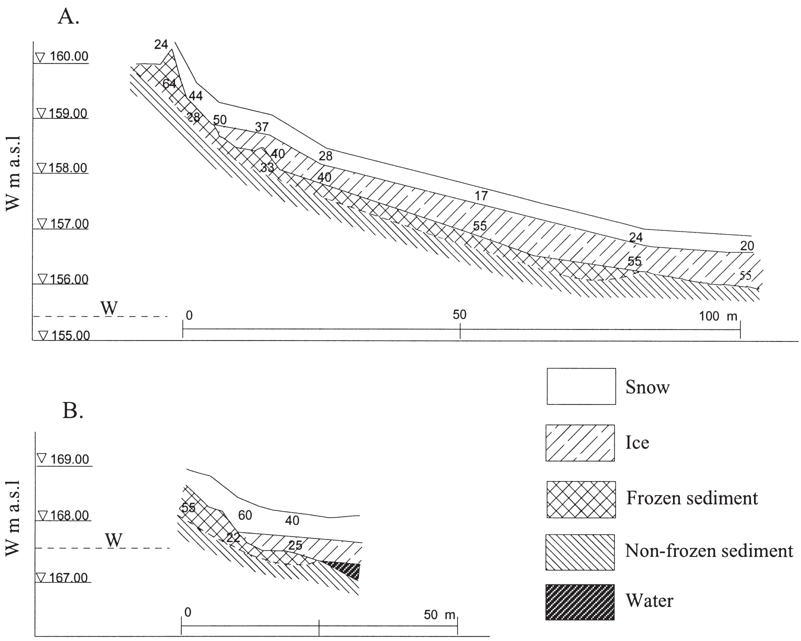

Fig. 4. Transect from (A) RLO (Oi3) and (B) NLL (Li3) in the middle of April 1986. The thicknesses of the different layers of snow, ice and frozen bottom sediment are presented in centimetres. W = observed water level.

$$D_f = (W_{om} - W_f) + (0.9 \times I_s) \quad (9)$$

where: W_f = mean water level on the last date of observed surface sediment freezing, I_s = thickness of shore ice, 0.9 = specific weight of ice.

The lowest level of the non-frozen ice pressure zone (D_p) is calculated as:

$$D_p = (W_{om} - W_{il}) + (0.9 \times I_s) \quad (10)$$

where W_{il} = mean lowest water level of the ice-covered period.

On minerogenic bottom, the mean depth of the frozen zone (D_f) was 1.64 m in RLO and 0.64 m in NLL (Table 2). On the average the last date of sediment freezing was 6 February in RLO and 22 January in NLL. The mean depth of the non-frozen ice pressure zone (D_p) was 3.66 m in RLO and 0.73 m in NLL.

To obtain a more general view of the ice effect, duration curves similar to those made for water level fluctuation were generated (Fig. 6). In RLO, the duration curves of the frozen (d_f) and non-frozen ice pressure (d_p) zones were clearly separated, while in NLL they were difficult to distinguish from each other.

Table 2. Ice conditions on different shores of the research lakes. D_{fo} = Lowest observed depth (m) of the frozen ice pressure zone, T = date when the ice touched the lowest depth (m) of the frozen ice pressure zone, I_s = mean thickness of shore ice (cm).

	1984–85		1985–86		
	D_{fo}	T	D_{fo}	T	I_s
RLO					45
Sandy shores (n = 3)	1.33	9 Feb.	1.98	9 Feb.	
Moraine shores (n = 5)	1.13	5 Feb.	1.76	4 Feb.	
Peaty shores (n = 3)	1.13	5 Feb.	–	–	
NLL					47
Sandy shores (n = 4)	0.64	16 Jan.	0.65	31 Jan.	
Moraine shores (n = 3)	0.62	13 Jan.	–	–	
Peaty shores (n = 2)	0.59	11 Jan.	0.81	17 Jan.	

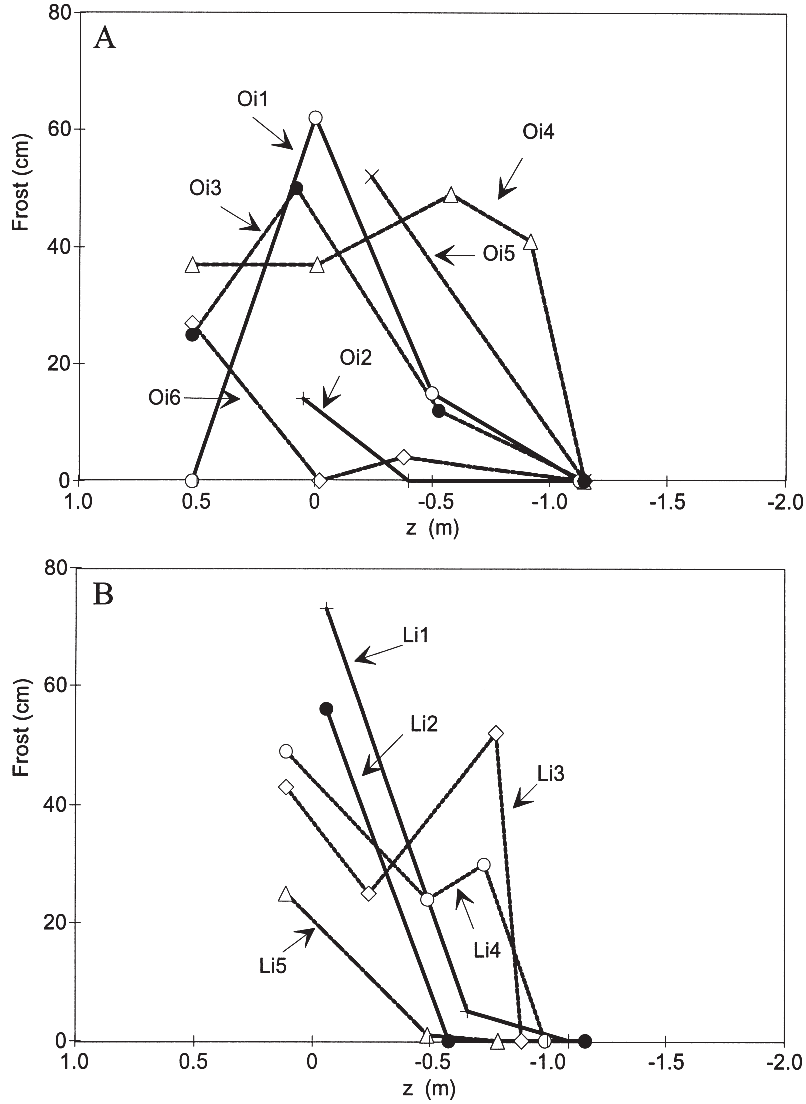

Fig. 5. Thickness of the frozen bottom sediment on different shores during the winter 1984–85. — A: In RLO, Oi1–2 are moraine shores, Oi3-5 are sandy shores and Oi6 is a peaty shore. — B: In NLL, Li1–2 are moraine shores, Li3–4 are sandy shores and Li5 is a peaty shore.

Geomorphology of the shores

Moraine shores are common in both lakes, although rocky shores are most abundant in NLL (Table 1). Sandy and peaty shores are in minority in both lakes. The rocky shores are usually eroded below the mean water level, and the physical difference in the bottom material composition between rocky and moraine shores is therefore small.

In RLO, sandy shores (O1, O3, O5) were clearly less stable than moraine ones (O2, O12), where almost no drifting of the material was revealed by sedimentation measurements (Fig. 7). Instead, values of ignition loss were higher on moraine shores compared to sandy ones. In NLL, the shores were more stable and most of the trapped sediments consisted of organic matter. Unstable bottom was only seen on sandy shores (L1, L7, L51). In RLO, only a slight negative correlation of the dry matter content of trapped sediment with fetch and depth was observed (Table 3). In NLL, a clear negative correlation with depth and a slight positive correlation with fetch emerged, and the material trapped by the sediment samplers was also mainly organogenic. In RLO, the eroded material was mainly minerogenic and not so clearly related to the physical factors as in NLL.

The subaquatic slopes of sandy and moraine

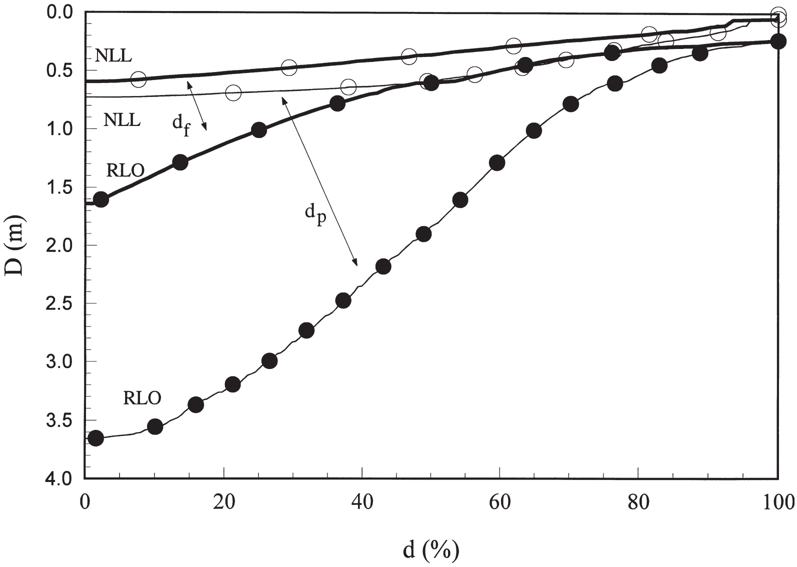

Fig. 6. Duration of the frozen ice pressure zone (d_f, thick line) and the non-frozen ice pressure zone (d_p, thin line) on the minerogenic shores during the winters 1984–85 and 1985–86. RLO = filled dots, NLL = open dots.

Table 3. Pearson's correlation coefficients between some environmental factors and the amount of dry matter (g m^{-2}) measured in sediment samples.* = $p < 0.05$, ** = $p < 0.01$.

	RLO	NLL
Number of obs.	22	24
Fetch (F_e), km	– 0.20*	0.44*
Slope (S_m), %	0.02$^{n.s.}$	– 0.43*
Depth (D), m	0.46*	0.52**
Ignation loss, %	– 0.27$^{n.s.}$	– 0.55**

shores are steeper in RLO than in NLL (Table 4). The difference is statistically significant in the uppermost part (S_1) of sandy shores ($p < 0.01$). The mean slope (S_m) of moraine shores is also significantly steeper in RLO ($p < 0.05$), while peaty and rocky shores have quite similar slopes in the two lakes.

Exposure at shoreline

Exposure measured as effective fetch (F_e) and as

Table 4. Mean values of slopes (S) of the different shore types and t-statistics between the study lakes. * = $p < 0.05$, ** = $p < 0.01$. F_e = fetch, S_1 = slope (0–1 m), S_2 = slope (1–2 m), S_m = slope (mean).

Shore material		*n*	F_e (km)	S_1 (%)	S_2 (%)	S_m (%)
Sand	RLO	17	1.9	7.6	4.2	5.1
	NLL	21	1.7	3.6	8.5	4.3
	t-test		– 0.67	– 4.10**	1.54	– 0.77
Moraine	RLO	15	2.3	9.9	12.5	10.3
	NLL	20	2.1	7.9	8.5	6.5
	t-test		– 0.27	– 1.00	– 1.29	– 2.44*
Rocky	RLO	5	2.9	16.9	11.5	11.8
	NLL	6	2.0	10.9	16.8	12.5
	t-test		– 1.33	– 0.74	0.88	0.06
Peat	RLO	5	0.6	4.7	1.1	1.7
	NLL	5	0.6	2.3	4.9	1.6
	t-test		0.00	– 3.98	1.01	– 0.14
Total	RLO	52	1.9	8.5	7.3	6.9
	NLL	53	1.8	5.9	8.9	5.7
	t-test		– 0.33	– 2.10*	0.92	– 1.2

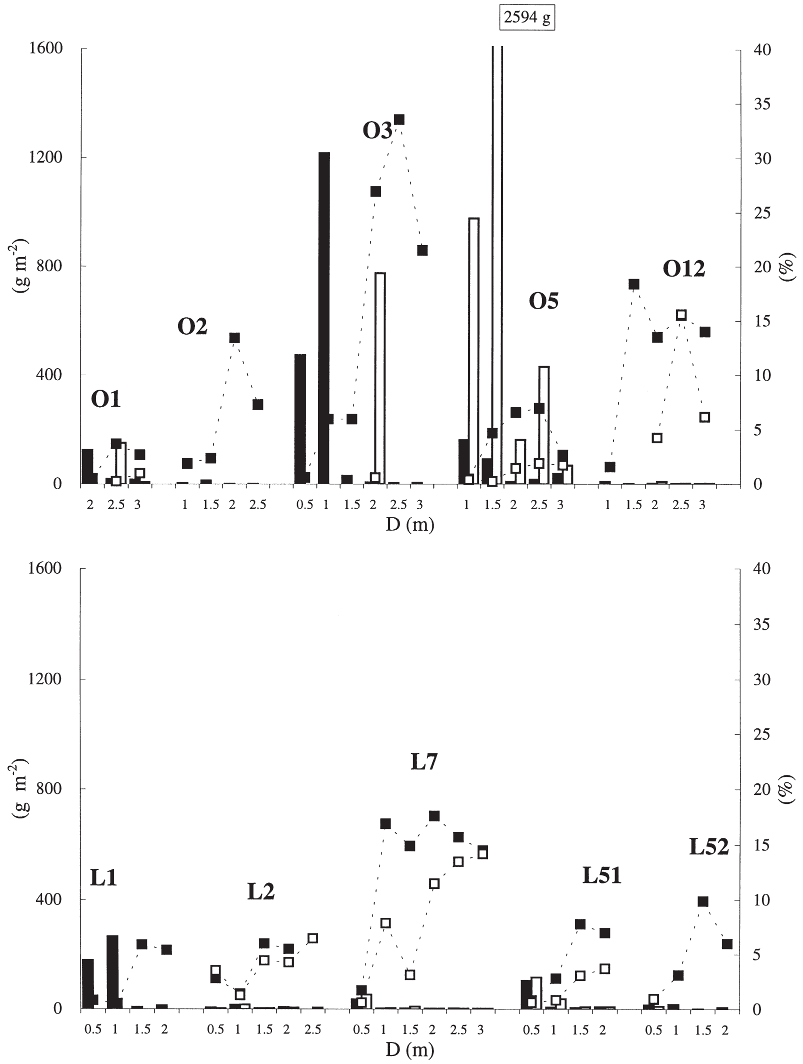

Fig. 7. Total sedimentation of dry matter (g m^{-2}, columns) and amount of organic matter measured by ignition loss (%, squares) on different transects in July (black symbols) and August (white symbols) in summer 1985. Upper panel = RLO, lower panel = NLL. See Appendix for detailed data on transects.

the shape (C) of the shoreline is presented in Appendix. The correlations between F_e and both shape values ($C_{0.5}$, C_1) were statistically highly significant ($p < 0.001$, Table 5). The sedimentation depth (D_s) correlated significantly with slope ($p < 0.01$), but there was no correlation between D_s and the variables reflecting exposure. When the lakes were considered separately the correlation between S_2 and D_s was clear ($r = 0.4617$*) in NLL, whereas it was not statistically significant in RLO ($r = 0.4653$).

Bottom quality

The cumulative distribution of different bottom substrates shows (Fig. 8) that a stony upper littoral is common in NLL, whereas in RLO the submerged, previously terrestrial part of the shore ($z > 0$ m) is still partly covered by peat. Sandy bottoms are common in both lakes, but the share of muddy bottoms is slightly higher in NLL. Bottom quality was quite clearly related to depth, with the exception of sandy bottoms, which were found in all depth zones.

In the discriminant analysis, most of the predicted and observed bottom substrate classes were the same, with the exception of gravel, which seems to be quite independent of depth and whose distribution is, therefore, difficult to predict (Table 6). Similarly, only one third of the sandy bottoms were predicted correctly. Only 41% of the 6 303 bottom quality quadrats were classified correctly. When the analysis was run separately for the two lakes, the results were

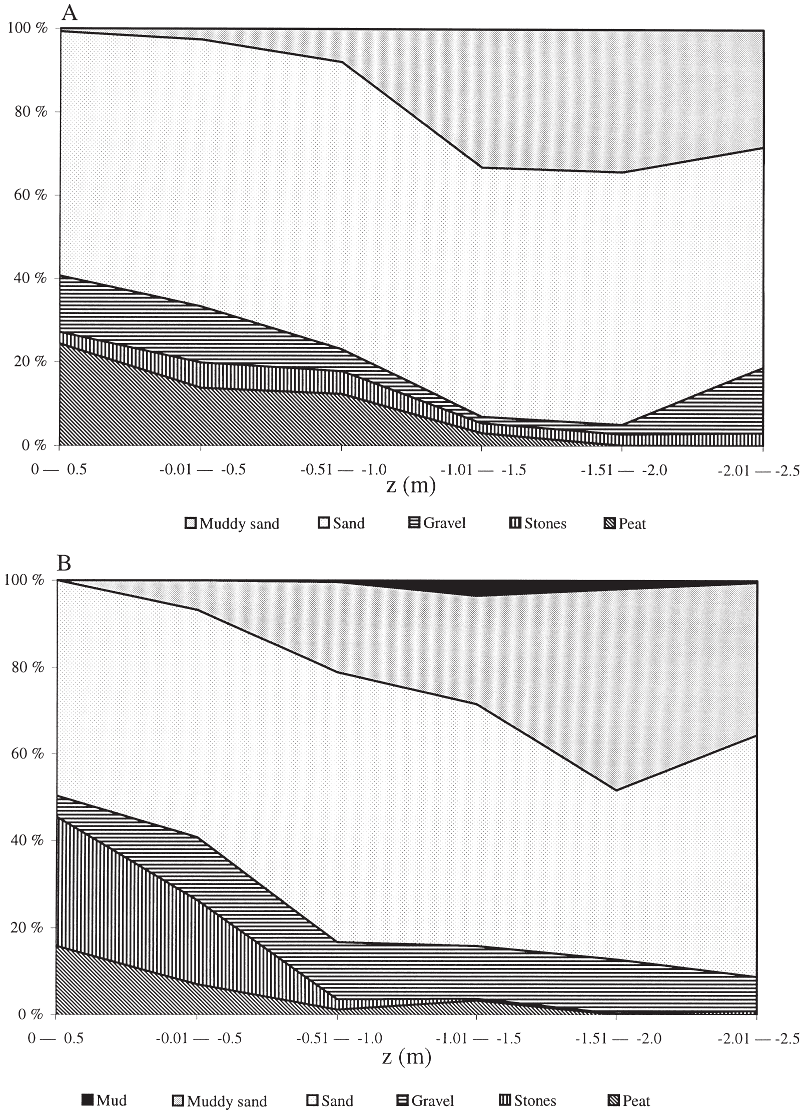

Fig. 8. Bottom quality distribution calculated as average values of all observations in different depth zones. — A: RLO, $n = 2\,699$, — B: NLL, $n = 3\,556$.

Table 5. Correlation matrix of the factors affecting sedimentation ($n = 107$). D_s = sedimentation depth, F_e = fetch, S_2 = slope (1–2 m), $C_{0.5}$ = shape (0.5 km circle), C_1 = shape (1 km circle). * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

	D_s	F_e	S_2	$C_{0.5}$	C_1
D_s	1.0000	0.0615	0.4104**	0.1981	0.0195
F_e		1.0000	– 0.0865	0.5144***	0.7220***
S_2			1.0000	0.2386	– 0.0392
$C_{0.5}$				1.0000	0.5341***
C_1					1.0000

not significantly better: 43% and 52% of the cases were classified correctly in RLO and in NLL, respectively.

The use of the predictive properties of discriminant analysis according to Moss *et al*. (1987) offers a rough method for estimating the bottom quality class in terms of environmental factors. As an example of the method, two typical transects from the studied lakes are presented in Fig. 9. The predictive model is generally able to show the basic depth-related distribution of bottom substrate.

Estimation of underwater light climate

The relationships between the intensity of red light (L_D) and depth (D) in the research lakes are presented in Fig. 10. In RLO, the depth of the zone (D_r) reached by 4.5% of incident red light is 2.12 m (A = 65 mg Pt l^{-1}). In NLL, D_r is 2.30 m (A = 54 mg Pt l^{-1}). The differences in the underwater light climate between the lakes were relative small, because the calculations were based exclusively on water quality. Consideration of the fluctuating water level would have expanded the area of the euphotic zone in RLO (cf. Rørslett 1984).

Discussion

Factors related to fluctuating water level

The vertical gradient related to depth constitutes the basis for the zonation of biota in the littoral area (Hutchinson 1975, Spence 1982). In regulated lakes, a precise determination of depth is quite essential due to the increased water level fluctuation. From the ecological point of view, it is important to distinguish between depth measured from the mean water level (MW) and actual observed depth. In several studies, Rørslett (1984, 1985, 1987ab, 1988) pointed out the importance of using a fixed Eulerian co-ordinate $D_{(z)}$ system instead of a moving Lagrangian co-ordinate $D_{(v)}$ system when assessing the effects of water level fluctuation. This means simply that depth is calculated from the median water level, not from a transient surface level (Rørslett 1988). In my study, Eulerian depth was used as the depth (D) calculated from W_{om}.

In regulated lakes, the effects of water level fluctuation can be divided into three ecologically important factors: (1) The raised water level at the beginning of the regulation increases shore-

Table 6. Distribution of the different bottom quality classes according to discriminant analysis (n = 6 303).

Observed bottom quality	n	Predicted bottom quality: Peat	Stones	Gravel	Sand	Muddy sand	Mud
Peat	287	162 56.4%	21 7.3%	1 0.3%	35 12.2%	58 20.2%	10 3.5%
Stones	261	71 27.2%	106 40.6%	22 8.4%	44 16.9%	9 3.4%	9 3.4%
Gravel	599	74 12.4%	94 15.7%	93 15.5%	111 18.5%	35 5.8%	192 32.1%
Sand	3 625	464 12.8%	325 9.0%	255 7.0%	1 119 30.9%	436 12.0%	1 026 28.3%
Muddy sand	1 482	24 1.6%	26 1.8%	7 0.5%	168 11.3%	1 062 71.7%	195 13.2%
Mud	49	0 0.0%	0 0.0%	8 16.3%	0 0.0%	0 0.0%	41 83.7%

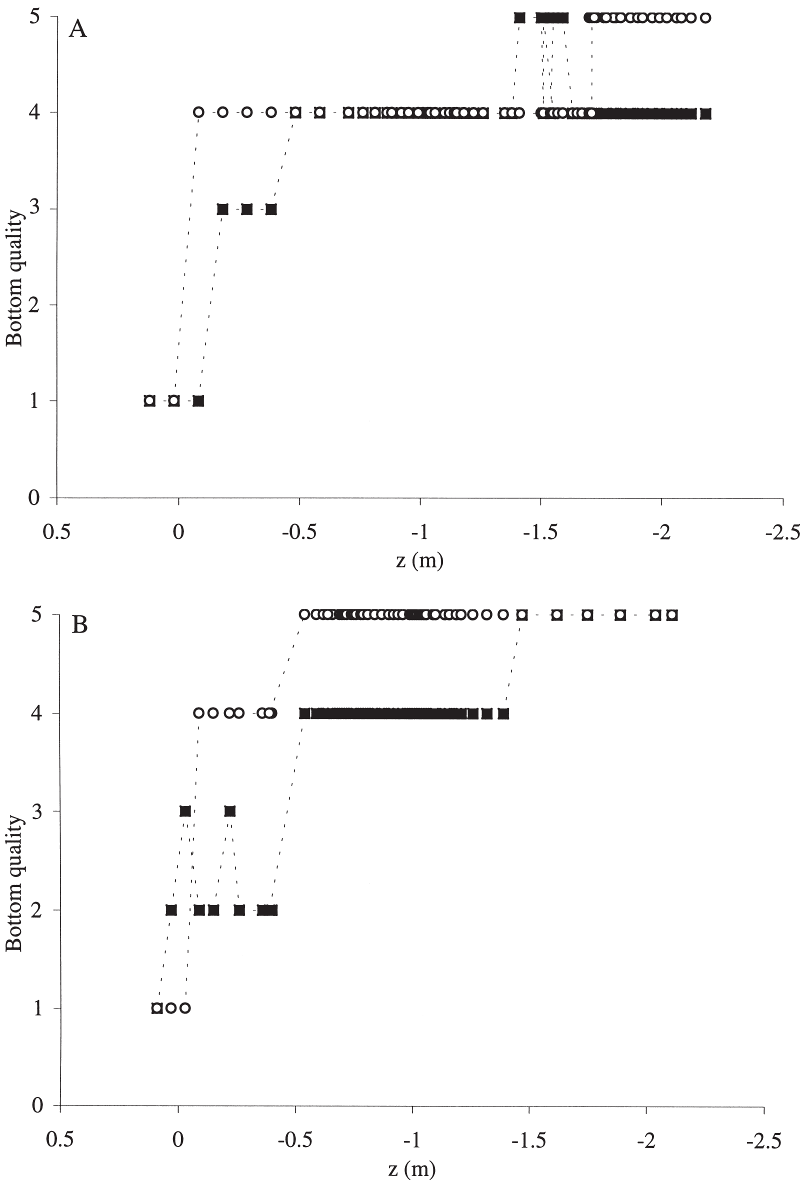

Fig. 9. Observed (filled squares) and predicted (open dots) bottom quality classes in (A) RLO, transect O27 and in (B) NLL, transect L08. 1 = peat, 2 = stones, 3 = gravel, 4 = sand, 5 = muddy sand.

line erosion. If the regulated water level is above the former mean highest water level (MHW), rapid erosion of the shoreline takes place (Hellsten and Alasaarela 1984). In regulated lakes, where the mean open water level (W_{om}) is below the former MHW, scouring effects are only observed on steep sandy shores (Hellsten and Alasaarela 1984). In RLO, the uppermost level of regulation (HW) is only 0.1 m above the former MHW, but the difference between unregulated and regulated W_{om} is appr. 0.8 m. The extensive erosion processes in the littoral of RLO are largely explained by the raise of W_{om}. The effects of the raised water level on erosion will be explained later in this paper.

Erosion processes can also alter the water quality, as has been shown in many studies on man-made reservoirs (Vogt 1978). Changes in water quality are caused by a breakdown of organic matter and a release of phosphorus from flooded ground (Hellsten *et al.* 1993). In regulated lakes, the changes in water quality are quite small and the flood effect lasts for a relatively short time (1–3 years). However, distinct changes have been seen in Lake Ransaren in Swedish Lapland (Rodhe

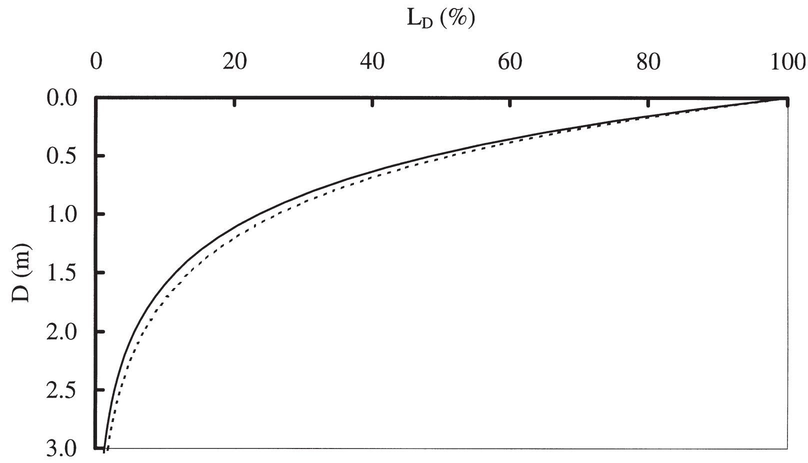

Fig. 10. Calculated intensity of red light (L_D) at different depths. Solid line = RLO, dotted line = NLL.

1964). The more nutrient-rich water quality observed in RLO is obviously caused by the drainage area with extensive peatlands, which have been intensively drained during the recent decades.

(2) The annual dynamics of water level fluctuation is an important factor affecting shore biota. Apart from the wintertime decline of the water level in regulated lakes, which has remarkable effects that will be discussed later in this paper, the water level fluctuation during the open water period is also important. Within the boreal zone, the typical water level curve of a non-regulated lake includes a sharp and rapidly declining spring flood peak after a late winter minimum (Fig. 2). The water level decreases quite slowly during the open water period, except for a shallow flood peak in autumn. The rhythm of water level fluctuation is quite similar to this in Sweden (Sundborg 1977, Nilsson 1981), Canada (Le Groupe Dryade ltée 1978) and Norway (Rørslett 1988).

Rørslett (1988) also calculated the cumulative distribution function (cdf) of water level for different Norwegian lakes. He divided the lakes into semi-natural lakes, short-time regulated lakes and storage reservoirs. The cdf-curves of the regulated lakes differed notably in shape from those of the lakes in a natural state. A comparison of these curves to Fig. 3. shows that NLL belongs to the group of semi-natural lakes, while RLO is clearly a storage reservoir, although the calculation methods used by Rørslett (1988) differ from the one used here.

The supralittoral in RLO is narrow, which means that wave erosion during the high water period is annually focused on the same area of the littoral and keeps the erosion processes active (Fig. 3). In NLL, the supralittoral zone is wide and resistant to water level fluctuation with flood-tolerant vegetation (including sedges and willows). On the other hand, the eulittoral zone, where the water level fluctuation usually takes place, was 26 % wider in RLO than in NLL, increasing the transportation of eroded material in the littoral (Figs. 3 and 7).

In RLO, the transition of the flood peak from the end of May to the beginning of June is ecologically important. It reduces the growth of shore vegetation, because many species cannot tolerate prolonged submersion. Also, the high autumnal water levels observed in RLO during the research period increase erosion effectively due to a lack of sheltering vegetation in the littoral. On the other hand, the “late flood” may also have a positive effect on sheltered gently sloping shores, because the degrading organic matter (old vegetation residue, etc.) is not flushed away from the littoral during the spring. It is hence available to the growing plants as a source of nutrients before the water level rises.

(3) The amplitude of water level fluctuation is not so important from the viewpoint of littoral ecology as the changes in W_{om} or the water level dynamics. Rørslett (1988), for example, did not find any correlation between erosion and the range of regulation. On the other hand, the amplitude is clearly related to the effects of the descending ice cover, because the lowest water level is usually reached during the winter.

The overall effect of ice on the littoral zone can be divided into active and passive factors. The active factors, such as expansion and drifting ice, seem to have a minor effect in the research lakes. Expansion of ice is mainly driven by fluctuating temperatures during the winter (Alestalo and Häikiö 1979, Gatto 1982). A similar effect was observed during the late autumn 1985, when the water level was raised in ice-covered RLO by 0.28 m (Fig. 2). This caused ice expansion and penetration into the soft sediments in the shore areas. Significant ice erosion also occurs at the break-up of the ice, if the wind pushes driven ice against the shoreline (Gatto 1982). Due to the low water level during the ice-breaking period in RLO, this phenomenon seldom takes place. Instead, the spring flood from the land areas (brooks, melting ice) commonly causes flushing of the fine and organic sediments into the deeper part of the littoral, but the importance of this phenomenon is difficult to estimate.

Ice affects passively by pressing against the bottom sediment during the winter causing both freezing of the sediment and mechanical pressure deeper in the littoral as decribed earlier in this paper. These effects are obvious in regulated lakes, where an effective drawdown of the water level allows wide areas to be affected by lowering ice (Quennerstedt 1958). As it was shown in the previous sections the bottom is also frozen in the uppermost zone of this area (frozen ice pressure zone), but the thickness of the frozen bottom varies greatly (Fig. 5). In the lower zone, ice just presses on the bottom (non-frozen ice pressure zone). In natural lakes, these zones are narrow and difficult to discern. From the ecological point of view, however, it is important to distinguish between these two zones, because many aquatic organisms tolerate the pressure of ice, even though they cannot resist freezing (Huusko *et al.* 1989, Tikkanen *et al.* 1989).

In a study on Swedish reservoirs, Nilsson (1981: his fig. 3) pointed out that the sediment is partly frozen during the winter. The same author did not report the lowest level of the frozen zone, but according his figs. 3 and 6 the frozen zone reached the level of 390 m a.s.l., where water was during January 1979 (Nilsson 1981). Relationship between the time and the lowest level of frozen sediment resembles the situation in RLO. Erixon (1979, 1981) and Renman (1989, 1993) described the freezing of the bottom in northern Swedish riverside lagoons with quite a wide water level amplitude. In his latest study, Renman (1993) described two zones functionally similar to those seen in my study lakes. Renman (1993) also found the frozen sediment (tjaele) to be 40 cm thick, which is near the values measured in RLO (Fig. 5.) Erixon (1981) did not calculate the lowest limit of the frozen zone, but it was near to the water level observed in February in the riverside lagoons.

Rørslett (1984, 1985, 1987a, 1988) conducted extensive investigations on ice scouring in Norwegian lakes. He estimated a normalised ice-scouring stress IS(z), which is calculated from the water level and ice thickness data. The stress function is scaled so that its maximum value is 100% for each lake. In semi-natural lakes, the function has one peak, but in storage lakes the shape of the function is typically two-peaked (Rørslett 1988). Rørslett (1984, 1985, 1987a, 1988) did not distinguish different zones, but only described ice scouring stress as a time-domain function. He found erosional marks on the lake floor, but was not able to separate ice scour from sublacustrine erosion caused by waves (Rørslett 1988). From the point of view of the observations made on RLO and NLL, the term "ice scouring" can be misleading for lakes with gently sloping shores, where the ice merely presses on the bottom. For example, the steel rods used to mark permanent plots (Hellsten and Riihimäki 1996) in RLO rarely fell down or disappeared during the winter, which shows that the ice cover is quite stable.

Erixon (1981) pointed out four factors which affect bottom freezing: the degree of ground water seepage, the type of substrata, the inclination of the shore (subaquatic slope) and the actual water level at the time of the freeze-up. Climatic (temperature, snow cover, illumination etc.) and microclimatic (cardinal point, snow cover and its quality etc.) factors are also important. All of these factors, with the exception of ground water seepage, are also important in RLO and NLL, but the quantification of the effects of these factors is very difficult. Only Rørslett (1988) was able to calculate the effect of ice cover by using water level and ice cover data, but the frozen and unfrozen zones were not separated. The Swedish results showed a correlation between the date and the lower boundary of the frozen sediment zone (Nilsson 1981, Erixon 1981). As it was also shown here, the lowest level of the frozen bottom can be roughly estimated by using water level and ice thickness data.

Ice cover can also act as a chemical factor by increasing nutrient release (e.g. nitrogen and calcium) from the sediments (Renman 1993). In northern reservoirs, the ice pressure pumps out large amounts of interstitial water rich in nutrients and organic matter (Hellsten *et al.* 1993). In my research lakes, some release may take place on peaty shores.

Physical environment at the littoral

The geomorphologic erosion processes initiated by regulation are mainly associated with two factors related to the water level fluctuation and its amplitude. The former dictates the level of processes in the shore profile, while the latter affects the rate of these processes (Alasaarela *et al.* 1989b). In RLO, the elevated water level has eroded huge amounts of former shore material and transported it to deeper areas or along the shoreline, mainly during the first years of regulation. In some shore areas a 30-cm-thick layer of eroded fine sand covers coarse sand, which obviously consists of old surface sediment of RLO before the regulation. The same phenomenon on a smaller scale is obvious on the moraine shores of RLO, even though both erosion and accumulation are notably less significant compared to sandy shores.

A similar situation is seen everywhere in northern Finland whenever the water level is raised (Granberg and Hakkari 1980, Hellsten and Alasaarela 1984). In Lake Kemijärvi, the water level was raised by 2 m at the beginning of the regulation in 1965. All of the sandy and part of the moraine shores were still unstable after seventeen years of regulation (Hellsten and Joronen 1986). Similarly, Newbury and McCullogh (1984) observed massive shoreline erosion in the Southern Indian Lake reservoir (2 391 km^2) in Canada. The water level was raised by 3 m in 1976, which caused erosion processes especially on shores consisting of frozen silt and clay. The total yearly volume of shoreline material removed varied from 1 to 23 m^3 per m of shoreline, depending on the shore exposure, and no stabilisation was seen during the first five years of regulation, except on shores controlled by bedrock. Before the impoundment, 76% of the shoreline was bedrock-controlled, but after the impoundment this share declined to 14%. Newbury and McCullogh (1984) predicted that it would take at least 35 years to restore fine-grained shorelines to their pre-impoundment condition, whereas the predicted time for an area of granular deposits was 20 yrs. In northern Sweden, effective erosion caused by water level uplift was observed in reservoirs and regulated lakes (Rodhe 1964, Lindström 1973, Sundborg 1977). Sundborg and Norrman (1963) found instability of the shoreline after 20–30 years of regulation, but some processes may be significant even after 50 years, depending on the exposure. Nilsson (1981) found many unstable shores in the Gardiken reservoir in northern Sweden after 20 years of regulation. Mark (1987), and Mark and Kirk (1987) also described the erosion caused by a raised water level in reservoirs in New Zealand. Norwegian lakes are usually deeper and the range of regulation can be wide even without a rise in the water level. Rørslett (1988) found no statistical correlation of D_e (the lowest depth of observed erosional activity) to the extent of water level fluctuation. In Finland, the regulated lakes with an unchanged mean water level (W_{om}) period showed no signs of erosional activity, either (Hellsten and Alasaarela 1984).

In some lakes, the shores are unstable even under natural conditions. Bodaly *et al.* (1984) pointed out that less than 5% of the total shoreline was eroding in Southern Indian Lake before impoundment. Saukko (1985) reported geomorphologic changes and unstability on the shores of Lake Oulujärvi before the water level regulation. Erosion was stimulated by the incline of the Lake Oulujärvi basin after the glacial period, which caused a rise of the water level in the eastern part of the lake (Keränen 1985). Temporary high water levels (such as spring floods) may also increase shore erosion.

Similarly to the water level uplift, the drawdown of the summertime water level can also stimulate erosion processes. In Lake Oulujärvi, water level has been regulated downwards since 1951. Shore erosion decreased in the uppermost part of the littoral, but increased at the lower levels (Keränen 1985). A similar situation caused by lowered water levels has been described in New

Zealand (Mark and Kirk 1987).

In terms of erosion, regulated lakes can be divided into several stages. Rørslett (1988) distinguished a transient stage lasting for one or more decades and a persistent (long-term) stage. Vogt (1978) identified three stages in Finnish man-made reservoirs; a starting phase, an erosion phase and a balanced phase. The sandy shores of RLO were clearly in the erosion phase, where erosion processes dominate. Although the most effective changes took place during the first few years of regulation, the instability of the shores is still obvious. The stability of the shores measured by sediment samplers mainly represents a transient situation, because the accumulation and erosion processes fluctuate rapidly, depending on such factors as wind direction and water level. The larger proportion of sandy bottoms also indicates more marked erosion, whereas muddy bottoms mainly exist in areas with a stable environment (Fig. 8). In general, the littoral of RLO presents a transient state of erosion, whereas NLL has reached a stable state.

Slope affects bottom quality directly. Håkanson (1977) points out that fine deposits rarely stay permanently on slopes inclining by more than 4.6%. Similarly, Duarte and Kalff (1986) reported a clear correlation between slope and sediment stability; they used a slope value of 5.33% as a borderline between gently and steeply sloping shores. In the study lakes, slope also correlated sligthly with the sedimentation level, but there was no correlation between the fetch and sedimentation level. Rørslett (1987a) also found distinct signs of shelf slides at submerged terraces, but only at depths below 7 m.

Shores consisting of easily eroded materials (sand, silt, etc.) slope more gently than stony or rocky shores (Table 4). If the water level is altered, "new" shores are usually steeper than "old" shores, where erosion tends to decrease the slope (Keränen 1985). The time factor obviously explains the steeper sandy shores of RLO as compared to NLL.

Exposure (fetch) has a direct physical effect on organisms through waves and currents, and an indirect effect by altering the physical status of the bottom (Spence 1982). Exposure affects open shores more than sheltered shores (Håkanson and Jansson 1983). Håkanson (1977) distinguished three different zones of shore processes, namely Erosion, Transportation, Accumulation (hereafter ETA). An erosion zone prevails in the uppermost part of the littoral and it has no deposition of fine material. A transportation zone emerges where there is a discontinuous deposition of fine particles. Accumulation processes are therefore interrupted by erosion processes. In an accumulation zone, fine materials (grain sizes < 0.006 mm) deposit continuously. Håkanson and Jansson (1983) point out that the ETA model does not apply to areas of subaquatic slopes or shallow water or, especially, in small lakes. This explains the poor correlation between sedimentation level and fetch in my research lakes (Table 5). Rørslett (1987a) also found that the signs of erosion activity failed to correlate with ETA zones in Lake Tyrifjorden in southern Norway.

On the other hand, the shape of the shoreline corresponds fairly well to the shoreline exposure. The main division into convex (capes) and concave (bays) forms is basically also a division into erosional cape areas and accumulative bay areas, which represents ecologically two very different areas. For example, Palomäki and Hellsten (1996) demonstrated that shape ($C_{0.5}$) was a good predictor of the littoral macrozoobenthos biomass. In my study, the correlation between sedimentation level and shape was very low (Table 5).

The importance of bottom quality as an environmental factor of the littoral was pointed out early by several ecologists (Pearsall 1920, Luther 1951). As discussed earlier, bottom quality is determined by several factors. Undoubtedly, the shore material makes up a basis for the bottom quality, even though water as an erosive force tends to change shores of all kinds by sorting the sediment. It is almost impossible to find pure moraine shores in the littoral, because the finest particles have flushed away and moraine consists of stones, gravel and sand. The shores of NLL are therefore much stonier than the shores of RLO (Fig. 8). This phenomenon of "oligotrophication" is widely known from reservoirs (Vogt 1978, Koskenniemi 1987).

The important properties of the bottom substrate include stability, grain size, amount of organic matter and amount of nutrients. The visual five-scale classification used in my study describes quite well the basic types of bottom and is based

Fig. 11. Schematic integrated view of different environmental factors in the littoral zone. Refer to the text for details.

on the contents of organic matter, which correlates strongly with the water content and the softness of the sediment (Duarte *et al.* 1988, Håkanson and Jansson 1983, Keddy 1982). On the other hand, macrophyte vegetation can also actively affect bottom sediments, as it may act as a sediment trap or a biotechnical shelter of the shore (Raspopov *et al.* 1988). The dying part of the vegetation is deposited on the shoreline and increases the amount of organic matter in the sediments. Therefore, the possibilities to predict the bottom quality by environmental factors are very limited, as it was also shown by discriminant analysis in this study (Fig. 9).

Furthermore, the bottom substrate is affected by the water quality and biological productivity of the lake. More nutrient-rich water produces more organic matter and, therefore, organic-rich bottoms are more common in eutrophic lakes (Toivonen 1984).

Primary production is essentially dependent on light, which is thus one of the most important factors affecting the environmental conditions in the littoral (Spence 1982, Canfield *et al.* 1985, Chambers and Kallf 1985, Rørslett 1985). The underwater light conditions depend on incoming radiation, surface reflection, absorption capacity of the water and received insolation (Rørslett 1987b, 1996). In my study, extinction coefficients of red light, as shown by the spectral measurements of Eloranta (1978), were calculated from water quality data (colour of water). Red light penetrates deepest in waters with a brown colour (Eloranta 1978, Eloranta and Marja-aho 1983, Silvennoinen and Turunen 1991). The red part of light is also most effective for the photosynthesis of plants with chlorophyll a and b (Salisbury and Ross 1978). Despite the numerous limitations of using regression-based calculations (Rørslett 1996), such rough calculations provide a simple tool to predict the euphotic zone by general water quality data without any laborious field measurements.

Conclusions

Regulation of the water level does not introduce any new environmental factors affecting the lake littoral. All the factors present in unregulated lakes also exist in regulated lakes, even though their amplitude is greater and their timing is usually different compared to lakes in a natural state (Rørslett 1988). To simplify this complicated littoral system, the environmental factors have been divided into three groups as presented in Fig. 11.

The first group (I. Lake-specific factors) includes the durations of water level (d_w), the frozen ice pressure zone (d_f), the non-frozen ice pressure zone (d_p) and the intensity of red light (L_D). They all are related to the relative water level (z) or depth (D), which means that their values remain constant at same vertical level of the littoral within a given lake. All of these factors except light are heavily affected by the water level fluctuation. Their values can be easily used in evaluating the effects of different water level regulation practices (Hellsten *et al.* 1996a).

The second group (II. Shore-specific factors) consists of geomorphological factors (slope S, shape C) and effective fetch (F_e), which fluctuate quite randomly within a given lake. These horizontal shore-specific factors are mainly driven by geomorphological processes, which are only partly dependent on water level regulation. All of these factors are related to decreasing exposure.

The third group of environmental factors (III. Site-specific factor) is illustrated by the bottom quality, itself related to slope (S), shape (C) and fetch (F_e), but most clearly correlated to the water depth. The softness of the bottom usually increases along with increasing depth as well as decreasing exposure. The bottom quality is a site-specific factor, whose distribution is difficult to predict. In addition to these factors, the general soil types (moraine, glaciofluvial deposits, peatland, cliffs) of the area and the quality of water affect the formation of the bottom quality. Identification of these factors helps us to understand the diverse nature of the littoral with its different habitats.

Most factors affecting the littoral are clearly related to the water level fluctuation. The possibilities to alleviate the harmful effects of the water level regulation are therefore limited if the fluctuation is not reduced (Hellsten *et al.* 1996a). Another way to mitigate these effects is to use different restoration methods, such as shoreline protection by groins or stone walls erected on the shoreline (Hellsten *et al.* 1996b).

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Appendix. The transects studied in RLO (O01–O52) and in NLL (L01–L53), the research area, effective fetch (F_e), cardinal point (C_p), littoral slope (S_1, S_2, S_m), shape of the shoreline ($C_{0.5}$, C_1). Refer to Methods for details.

	Area	F_e km	C_p	S_1 %	S_2 %	S_m %	$C_{0.5}$°	C_1°
O01	Paloniemi	3.4	W	5.9	3	4	72	72
O02	Korpiniemi	2.6	NW	3.6	8.8	5.1	225	117
O03	Härkösärkkä	1.0	SE	12.5	9.1	10.5	45	45
O04	Petäjälahti	0.7	SE	5	1.1	1.8	56	18
O05	Eksyneenniemi	1.8	W	9.1	2.3	3.7	90	82
O06	Jänesuo	1.7	SE	0.9	1.2	1	68	42
O07	Vattusaari	3.4	E	1.3	7.6	2.2	185	115
O08	Veklo	1.2	SE	7.1	11.1	8.7	77	45
O09	Ärjä	1.8	W	9.1	1.6	2.7	155	136
O10	Kaisanlahti	0.3	W	5.3	0.7	1.2	22	13
O11	Tervasalmi	0.6	NW	4.8	0.9	1.5	35	17
O12	Katajalahti	1.2	NW	12.5	24	16.4	170	32
O13	Itkonkallio	3.4	S	3	3.8	3.4	170	65
O14	Matalanlahti	1.3	SW	1.9	2	2	75	52
O15	Kalliolahti	2.4	NW	14.3	4.2	6.5	50	50
O16	Leväniemi	2.0	NW	6.3	4.8	5.5	45	45
O17	Rakennusniemi	2.5	NW	9.1	10	9.5	167	42
O18	Unnukanlahti	0.5	N	5	2.3	3.2	68	13
O19	Riihiniemi	2.5	NE	14.3	19.3	16.4	180	176
O20	Karhuniemi	4.3	SE	2.5	3.6	3	162	130
O21	Ala-Honkinen	4.2	N	12.5	14.3	13.3	162	145
O22	Vattusaari	2.3	S	10	20	13.3	178	60
O23	Ylä-Honkinen	4.5	W	14.3	16.7	15.4	150	150
O24	Siikaniemi	1.3	S	14.3	6.7	9.1	122	110
O25	Lauttaräme	0.9	E	3.2	0.5	0.9	51	13
O26	Sopasenlahti	1.0	E	7.1	11.1	8.7	59	37
O27	Matinsalmi	1.1	E	5	2	2.9	90	22
O28	Katajalahti	1.6	NW	5.3	4	4.6	56	35
O29	Koukkulahti	0.6	N	14.3	4.5	6.8	65	13
O30	Hanhiniemi	0.5	N	12.5	20	15.4	18	18
O31	Halonen	2.0	SE	2.7	0.9	1.4	195	157
O32	Halmeniemi	1.0	NE	7.1	1.8	2.9	115	28
O33	Petäjäniemi	1.9	SE	10	1	1.8	125	62
O34	Ala-Honkinen	2.5	W	5.5	2	2.9	52	45
O35	Ylä-Honkinen	2.0	NW	7.1	3.3	4.5	50	50
O36	Saunasaari	2.0	E	6.3	9.1	7.4	49	49
O37	Hiekkaniemi	0.9	E	11.1	9.1	10	37	25
O38	Vattusuo	0.6	W	5	1.4	2.2	75	23
O39	Halonen	3.7	E	10	16.7	12.5	180	180

Appendix. (*continues*).

	Area	F_e km	C_p	S_1 %	S_2 %	S_m %	$C_{0.5}$°	C_1°
O40	Juurikkaniemi	4.2	E	1.4	7.7	2.4	127	90
O41	Pöytäsaari	4.4	Sw	14.3	20	16.7	210	130
O42	Lauttaniemi	0.3	W	10	12.5	11.1	9	7
O43	Karinniemi	2.1	W	4.5	5.6	5	220	80
O44	Kotiranta	2.4	N	6.3	5.9	6.1	100	54
O45	Korpiniemi	1.7	NE	14.3	3.1	5.1	122	98
O46	Pajasaari	0.4	W	11.1	5.9	7.7	32	–
O47	Hanhiniemi	1.3	NW	50	20	28.6	89	42
O48	Ala-Honkinen	3.0	NW	11.1	5	6.9	180	87
O49	Kaisaniemi	1.5	N	5.9	9.1	7.2	88	88
O50	Oraviniemi	0.8	W	9.1	7.9	8.5	132	36
O51	Härkösärkkä	1.0	SE	5.9	10	7.4	45	45
O52	Tervasalmi	0.6	NW	0.7	2.8	1.1	36	22
L01	Lehtolahti	2.7	SE	1.8	0.9	1.2	75	35
L02	Vasikkasaari	2.1	SE	5.9	6.6	6.2	185	47
L03	Ahvenlahti	0.9	S	0.7	0.4	0.5	32	31
L04	Timoniemi	1.1	NW	1.5	20	2.8	162	25
L05	Lehtosaari	0.8	SE	6.3	3.1	4.2	45	23
L06	Jysmänniemi	1.4	SW	1.7	1	1.3	62	50
L07	Hiekkakuottua	1.7	SE	1.9	4.5	2.7	50	47
L08	Selkälahti	0.2	SE	1.8	8.3	3	30	30
L09	Varissalo	0.6	N	5	0.6	1.1	52	9
L10	Kekkosenlahti	3.9	SE	2.1	5.9	3.1	82	67
L11	Selkäsaari	2.1	NW	3	3.1	3.1	100	100
L12	Puroniemi	4.2	NE	2.3	5.3	3.2	159	155
L13	Pitkämännikkö	4.9	NE	1.5	1.8	1.6	130	125
L14	Selkäsaari/N	2.8	NE	8.3	11.1	9.5	160	160
L15	Selkäsaari	1.1	S	1.6	1.1	1.3	45	45
L16	Jysmänniemi	3.2	SW	7.7	4.2	5.4	153	130
L17	Kuivaniemi	2.7	W	6.7	3.3	4.4	165	115
L18	Isohiekka	3.6	W	1.7	3.2	2.2	75	65
L19	PKalliolahti	3.6	NW	3.2	5.6	4.1	78	78
L20	Salonsaari	2.3	SW	8.3	11.1	9.5	125	103
L21	Lapinlahti	1.1	NE	6.3	10	7.7	98	78
L22	Kuivaniemi	2.3	N	12.5	6.7	8.7	172	71
L23	Vetokannas	0.8	NE	1.7	0.7	1	30	13
L24	Pärtölahti	1.1	W	2.3	2	2.1	92	36
L25	Matalanlahti	0.3	W	1	1.2	1.1	10	8
L26	Jauholahti	0.4	E	2.2	2.2	2.2	35	-
L27	Pukkisaari	2.8	W	8.3	3.2	4.6	125	125
L28	Saarenlahti	0.9	NW	1.5	20	2.8	46	22
L29	Hakolahti	1.0	W	2.6	2.4	2.5	160	35
L30	Lehtosaari	2.3	SW	3.4	7.7	4.7	100	100
L31	Selkälahti	0.1	E	4.3	1.4	2.1	27	27
L32	Niskasaaret/N	2.9	N	11.1	4.5	6.4	140	140
L33	Ukonsaari	1.2	SE	25	11.1	15.4	128	29
L34	Kumpulantalo	0.9	NW	3.2	50	6	57	25
L35	Tynisaari	1.4	W	20	12.5	15.4	182	142
L36	Halmekaarre	0.7	SW	20	12.5	15.4	60	8
L37	Lehmisaari	0.7	SE	11.1	8.3	9.5	68	50
L38	Salonsaari	1.6	SW	1.6	5	2.4	81	81
L39	Luotolahti	2.0	NW	2.7	6.7	3.8	75	38
L40	Varisniemi	3.4	W	14.3	25	18.2	161	82
L41	Niskasaaret/S	1.8	NW	9.1	33.3	14.3	42	23
L42	Kuivasaaret	1.3	NE	7.7	12.5	9.5	135	85
L43	Multipakka	0.5	N	14.3	20	16.7	72	-
L44	Marrasniemi	1.7	W	16.7	20	18.2	165	72
L45	Rimminkangas	1.0	E	3.2	50	6	157	33
L46	Timoniemi	1.8	SE	1.9	10	3.2	56	42
L47	Saarilahti	0.9	S	7.1	7.1	7.1	56	22
L48	Multipakka/S	0.6	SE	6.3	12.5	8.4	62	9
L49	Petäjäniemi	1.0	NW	5.6	4.2	4.8	35	27
L50	Karhuhiekka	4.7	NE	3	1.4	1.9	149	112
L51	Kotalahti	1.3	SW	1.2	1.5	1.3	89	34
L52	Lehtolahti	2.7	SE	2	3.3	2.5	82	41
L53	Selkälahti	1.6	SE	5	3.3	4	88	88

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