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A THREE-PARAMETER TROPHIC STATE INDEX FOR SMALL LAKES

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Abstract. Data of a complex research into the trophic state of small Estonian lakes, carried out during the period 1978–91 in 102 lakes of various type in SE Estonia, were used in developing a trophic state index. This index was based on the content of total phosphorus and chlorophyll *a*, and water transparency. Total phosphorus was chosen as the basic parameter. The range of the trophic scale for the studied lakes was from 12 to 120 mg P m^{-3}. According to the scale, the transition line from mesotrophy to eutrophy is between 22–23, and from eutrophy to hypertrophy, between 47–48 mg P m^{-3}.

Key words: lakes, trophic state index, total phosphorus, chlorophyll *a*, water transparency, Estonia.

INTRODUCTION

Classification systems of the trophic state of lakes, often based on a single parameter, mainly chlorophyll *a* content, have been suggested by Sakamoto (1966), the National Academy of Sciences (1972), Dobson et al. (1974). A single trophic parameter does not often reflect water quality adequately. Considering this, several investigators have focused on the elaboration of a quantitative system by correlating variables that reflect the trophic state of lakes and can be expressed in numerical terms (Shannon & Brezonic, 1972; Carlson, 1977; Walker, 1979). Our earlier trophic classification system (Milius et al., 1987) is based on chlorophyll *a* content and ten correlating parameters that reflect the trophic status.

The aim of this paper is to present a statistically developed method for the assessment of the trophic state of lakes by means of a trophic index. The index provides a single figure based on total phosphorus (TP), chlorophyll *a* (Chl), and water transparency measured by Secchi disk (SD). The content of TP was chosen as the basic parameter. Using this index, we assessed the trophic state of 102 small lakes.

INVESTIGATED LAKES

The lakes studied (Table 1) are mostly located in South-East and South Estonia (counties of Valga, Võru, Põlva, Tartu, Viljandi). Only a few lakes in the eastern part of the country (Jõgeva County) were studied. Lake surface areas varied considerably: from 0.6 to 707.6 ha; in most cases 5–100 ha. Mean depths ranged from 2 to 14 m and maximum depths from 3.5 to 33 m.

Table 1

SE Estonian small lakes on the trophic scale

Lake	Lake catal. No.*	Total phosphorus**, mg P m^{-3}	Chlorophyll *a***, mg m^{-3}	Water transparency**, m	Trophic index, mg P m^{-3}
1	2	3	4	5	6
Mesotrophic lakes					
Nohipalu Valgjärv	1297	14.1 ± 0.7; 22	2.1 ± 0.2; 39	6.6 ± 0.2; 39	12.60
Väike-Palkna	1517	19.3 ± 2.3; 2	1.9 ± 0.4; 4	5.2 ± 0.3; 4	14.80
Piigandi	1084	15.3 ± 0.7; 38	2.6 ± 0.2; 44	4.3 ± 0.1; 45	15.68
Inni	1200	14.4 ± 0.8; 23	3.1 ± 0.3; 24	4.1 ± 0.3; 19	16.27
Udsu	1177	17.1 ± 0.8; 30	3.1 ± 0.3; 34	4.5 ± 0.1; 34	16.68
Roksi	1170	14.6 ± 0.8; 18	3.3 ± 0.4; 17	4.0 ± 0.1; 18	16.69
Hino	1555	21.8 ± 3.8; 1	2.1 ± 0.5; 3	4.4 ± 0.4; 3	16.72
Peitlemäe	1054	15.2 ± 0.9; 17	2.6 ± 0.3; 16	3.4 ± 0.1; 15	16.90
Uiakatsi	1238	15.9 ± 0.7; 39	3.1 ± 0.2; 44	4.0 ± 0.1; 45	16.92
Pulli	1552	19.8 ± 1.9; 4	2.4 ± 0.4; 8	4.1 ± 0.2; 8	16.92
Saagjärv	1047	14.4 ± 0.8; 18	2.6 ± 0.3; 18	3.1 ± 0.1; 14	17.12
Koorküla Valgjärv	1180	16.7 ± 0.8; 30	3.5 ± 0.3; 34	4.2 ± 0.1; 34	17.48
Virtsjärv	1178	16.3 ± 0.9; 18	3.5 ± 0.4; 18	3.9 ± 0.1; 17	17.59
Tillijärv	835	13.6 ± 1.3; 4	3.4 ± 0.5; 7	3.1 ± 0.3; 7	17.82
Saadjärv	653	17.7 ± 0.8; 35	3.8 ± 0.3; 68	4.3 ± 0.1; 68	17.95
Viisjaagu	924	18.1 ± 1.8; 24	2.9 ± 0.3; 26	2.9 ± 0.2; 26	19.35
TõrvaVanamõisa	1000	14.8 ± 0.8; 16	4.5 ± 0.5; 20	3.0 ± 0.2; 20	19.67
Kisejärv	1532	21.9 ± 2.3; 3	2.9 ± 0.5; 5	2.8 ± 0.2; 5	20.77
Kooraste Kõverjärv	1232	21.5 ± 2.0; 4	3.3 ± 0.6; 4	2.9 ± 0.5; 4	20.92
Tõugjärv	1400	20.6 ± 3.2; 8	4.1 ± 0.6; 10	3.3 ± 0.2; 11	21.01
Liinjärv	1404	23.1 ± 3.2; 8	3.4 ± 1.0; 10	3.1 ± 0.2; 11	21.32
Rõikajärv	834	14.6 ± 1.4; 4	5.7 ± 0.9; 7	2.4 ± 0.2; 7	22.10
Rõuge Suurjärv	1403	23.0 ± 2.0; 8	4.2 ± 0.7; 10	3.1 ± 0.3; 11	22.17

Table 1 continued

1	2	3	4	5	6
		Eutrophic lakes			
Rõuge Valgjärv	1405	27.1 ± 3.2; 10	4.1 ± 0.5; 12	3.2 ± 0.2; 12	23.29
Rõuge Ratasjärv	1401	22.8 ± 2.8; 8	5.0 ± 1.1; 10	3.0 ± 0.2; 10	23.41
Prossa	568	23.8 ± 2.5; 3	4.2 ± 0.8; 5	2.7 ± 0.1; 5	23.56
Jõksi	1224	19.9 ± 0.9; 35	5.8 ± 0.5; 39	2.6 ± 0.1; 39	23.99
Agali	847	24.7 ± 1.1; 34	5.1 ± 0.4; 35	2.9 ± 0.1; 35	24.28
Kooraste Suurjärv	1236	22.1 ± 1.3; 13	4.8 ± 0.5; 15	2.5 ± 0.1; 15	24.29
Nõo Suur Karujärv	935	20.3 ± 3.5; 1	7.1 ± 1.6; 3	2.9 ± 0.3; 3	24.46
Tsolgo Pikkjärv	1282	28.5 ± 1.9; 9	5.1 ± 0.7; 9	3.1 ± 0.3; 9	24.94
Tuuljärv	1413	30.5 ± 10.8; 1	4.8 ± 1.1; 3	3.1 ± 0.2; 3	25.26
Kääriku	1059	20.7 ± 1.2; 18	6.5 ± 0.7; 18	2.5 ± 0.1; 17	25.39
Pühajärv	1053	23.9 ± 1.1; 36	5.4 ± 0.4; 36	2.6 ± 0.1; 30	25.39
Jaanuse	1038	24.1 ± 1.4; 18	6.0 ± 0.7; 18	2.7 ± 0.1; 18	25.48
Paidra	1284	25.3 ± 1.7; 9	5.6 ± 0.8; 9	2.7 ± 0.2; 9	25.57
Nõuni	1013	22.7 ± 1.2; 19	5.7 ± 0.6; 19	2.4 ± 0.1; 19	25.78
Pikrejärv	1171	23.3 ± 1.3; 21	6.0 ± 0.6; 21	2.5 ± 0.2; 19	26.06
Kavadi	1437	27.2 ± 2.9; 3	5.0 ± 0.9; 5	2.4 ± 0.1; 5	26.69
Kooraste Pikkjärv	1230	24.7 ± 1.6; 10	6.7 ± 0.9; 11	2.6 ± 0.1; 13	26.77
Karijärv	843	30.6 ± 3.8; 15	5.8 ± 0.8; 17	2.8 ± 0.1; 18	27.22
Kirikumäe	1447	31.8 ± 3.3; 3	3.8 ± 0.7; 5	1.8 ± 0.1; 5	28.64
Tornijärv	1057	22.1 ± 1.9; 5	9.2 ± 1.7; 5	2.3 ± 0.2; 5	28.68
Kasaritsa Verijärv	1381	31.3 ± 2.1; 15	6.2 ± 0.7; 17	2.4 ± 0.1; 17	28.94
Vaskna	1443	37.8 ± 6.6; 1	4.2 ± 0.9; 3	2.3 ± 0.1; 3	28.95
Vissi	727	29.9 ± 2.2; 6	6.0 ± 1.5; 8	2.1 ± 0.2; 8	29.88
Kuremaa	554	31.5 ± 2.5; 6	7.4 ± 1.1; 8	2.4 ± 0.2; 8	30.55
Vagula	1261	37.9 ± 2.6; 9	6.5 ± 0.9; 9	2.6 ± 0.1; 9	30.69
Kaussjärv	1402	28.6 ± 3.0; 10	6.8 ± 1.4; 12	1.8 ± 0.1; 12	31.83
Lavatsi	851	29.2 ± 1.2; 43	9.4 ± 0.7; 59	2.2 ± 0.1; 59	32.13
Kasaritsa Valgjärv	1380	32.6 ± 1.9; 13	9.2 ± 1.1; 13	2.1 ± 0.1; 13	33.94
Vasula	753	32.2 ± 2.1; 10	8.3 ± 1.0; 12	1.9 ± 0.2; 12	33.95
Kiidjärv	1107	39.7 ± 3.0; 7	7.1 ± 1.1; 7	2.1 ± 0.2; 7	34.43
Erastvere	1228	38.5 ± 2.0; 21	9.8 ± 0.9; 23	2.4 ± 0.1; 23	34.72
Holstre	904	43.3 ± 4.2; 4	7.1 ± 1.2; 6	2.0 ± 0.1; 6	35.56
Otepää Valgjärv	1077	34.4 ± 3.7; 3	9.7 ± 2.2; 3	1.9 ± 0.1; 3	36.34
Vidrike	1203	43.8 ± 2.8; 11	8.6 ± 1.0; 13	2.0 ± 0.1; 13	37.28
Petajärv	1166	39.7 ± 2.0; 23	8.6 ± 0.8; 23	1.7 ± 0.2; 23	38.06
Kuningvere	588	37.5 ± 3.2; 5	10.3 ± 1.5; 8	1.8 ± 0.2; 8	38.26
Laanemetsa	1179	34.1 ± 2.0; 18	8.6 ± 1.0; 18	1.4 ± 0.1; 17	38.33
Kurnakese	1037	42.9 ± 2.5; 18	8.8 ± 1.0; 18	1.8 ± 0.1; 17	38.42
Elistvere	651	25.5 ± 2.7; 3	14.1 ± 3.2; 3	1.5 ± 0.2; 3	38.58
Vellavere Külajärv	925	38.2 ± 2.6; 26	10.8 ± 1.5; 28	1.8 ± 0.1; 28	38.80

1	2	3	4	5	6
Viljandi	828	35.9 ± 3.8; 3	13.7 ± 3.0; 3	1.9 ± 0.2; 3	39.43
Pangodi	1006	34.3 ± 1.6; 35	11.8 ± 1.0; 36	1.6 ± 0.1; 36	39.68
Karsna	1275	44.3 ± 3.0; 9	8.2 ± 1.1; 9	1.5 ± 0.3; 9	40.84
Kubija	1378	31.7 ± 2.2; 9	14.0 ± 1.8; 11	1.5 ± 0.1; 11	41.49
Väike-Juusa	1041	36.5 ± 2.1; 18	13.1 ± 1.5; 17	1.6 ± 0.1; 17	41.58
Otepää Kärnjärv	1051	35.6 ± 1.9; 24	13.6 ± 1.4; 24	1.6 ± 0.1; 23	41.64
Mäha	1048	44.9 ± 2.3; 24	11.1 ± 1.1; 24	1.7 ± 0.1; 23	41.72
Verevi	932	46.3 ± 2.0; 45	11.4 ± 0.8; 51	1.8 ± 0.1; 51	41.99
Annejärv	1277	54.3 ± 3.7; 9	11.0 ± 1.6; 9	1.9 ± 0.1; 9	43.34
Saare	573	33.0 ± 2.8; 5	17.5 ± 2.7; 7	1.4 ± 0.1; 7	44.33
Kaiavere	571	41.9 ± 9.5; 3	14.4 ± 3.2; 3	1.6 ± 0.2; 3	44.80
Partsi Kõrtsijärv	1128	46.9 ± 5.8; 8	11.4 ± 2.1; 8	1.5 ± 0.1; 8	44.80
Vana-Koiola	1249	50.4 ± 3.5; 9	13.7 ± 1.9; 9	1.7 ± 0.1; 9	46.10
Pilkuse	1042	44.1 ± 2.5; 18	14.7 ± 1.7; 18	1.5 ± 0.1; 17	46.12
Kaarepere Pikkjärv	569	34.8 ± 3.7; 3	21.2 ± 3.8; 5	1.5 ± 0.1; 5	46.53
Kadastiku	1184	45.6 ± 2.6; 18	10.2 ± 1.2; 18	1.1 ± 0.0; 18	47.86
Raigastvere	650	35.1 ± 3.8; 3	19.5 ± 4.4; 3	1.3 ± 0.2; 3	48.78
		Hypertrophic lakes			
Tamula	1262	56.2 ± 3.9; 9	14.2 ± 2.0; 9	1.6 ± 0.2; 9	49.20
Jääva	1173	55.2 ± 3.2; 18	17.4 ± 2.0; 18	1.7 ± 0.2; 18	49.97
Juusa	1055	55.0 ± 2.4; 45	16.4 ± 1.2; 46	1.4 ± 0.1; 46	52.90
Lasva	1290	71.0 ± 4.7; 10	13.8 ± 1.9; 10	1.5 ± 0.1; 10	53.52
Linaleojärv	1289	71.8 ± 4.1; 18	14.8 ± 1.7; 18	1.6 ± 0.2; 18	53.66
Holstre Linajärv	902	65.6 ± 6.3; 4	14.1 ± 2.3; 7	1.4 ± 0.1; 7	54.25
Väike-Kodijärv	1010	54.2 ± 5.8; 3	21.4 ± 4.8; 3	1.4 ± 0.1; 3	55.62
Põlva Reservoir	1001	86.1 ± 5.9; 5	7.3 ± 4.1; 5	1.0 ± 0.2; 5	56.17
Piigandi Mustjärv	1103	55.6 ± 4.4; 5	12.3 ± 3.2; 5	0.9 ± 0.05; 5	57.63
Kodijärv	1009	61.1 ± 3.2; 20	23.2 ± 2.3; 21	1.3 ± 0.1; 21	60.28
Holvandi Kivijärv	1120	52.9 ± 4.9; 5	18.8 ± 6.4; 5	0.7 ± 0.1; 5	65.93
Ruusmäe	1537	161.3 ± 28.1; 1	13.7 ± 3.1; 3	1.7 ± 0.3; 3	66.91
Partsi Saarjärv	1263	58.1 ± 2.9; 5	14.9 ± 4.7; 5	0.6 ± 0.1; 4	70.66
Kokora Mustjärv	587	75.1 ± 6.0; 6	33.0 ± 5.5; 6	1.1 ± 0.1; 6	71.97
Meelva	1136	84.3 ± 12.8; 5	18.4 ± 3.5; 5	0.7 ± 0.1; 5	77.67
Laose Valgjärv	831	161.0 ± 17.4; 3	15.2 ± 2.4; 7	1.1 ± 0.3; 7	79.46
Kriimani	948	100.5 ± 5.5; 43	31.7 ± 3.4; 57	1.0 ± 0.1; 57	84.60
Kooraste Linajärv	1233	116.2 ± 5.2; 36	30.4 ± 2.4; 41	0.8 ± 0.1; 42	91.76
Otepää Pikajärv	1078	137.4 ± 6.5; 29	46.7 ± 4.1; 31	0.8 ± 0.1; 31	106.17
Pikamäe	1129	101.9 ± 22.7; 5	14.1 ± 3.7; 5	0.5 ± 0.1; 5	106.17
Viroste	1123	96.7 ± 16.6; 5	35.5 ± 22.2; 5	0.5 ± 0.1; 5	108.17
Pappjärv	1379	171.3 ± 7.9; 33	54.5 ± 4.4; 39	0.8 ± 0.1; 39	120.40

* After Kask, 1964.
** Data presented as $\bar{x}$ ± SE; *n*.

The lakes were mostly light-coloured (water colour up to 50° on the scale of $CoSO_4$-$K_2Cr_2O_7$ standard solutions). Brownish-coloured lakes such as Vidrike, Mäha, Kurnakese, Otepää Kärnjärv, whose average colour was 60°, and Laanemetsa and Kadastiku, whose colour exceeded 100°, were examined in 1987–90. In 1991 several lakes (Piigandi Mustjärv, Holvandi Kivijärv, Partsi Saarjärv, Meelva, Pikamäe, Viroste) had very dark water, the colour range being 210–400°. The darkest water (350–400°) and the lowest visibility (SD 0.3–0.7 m) were recorded in L. Viroste. The above-mentioned lakes have, as a rule, very low SD (below 1 m) because of their reddish-brown water.

The N:P ratio of the majority of lakes under study ranged from 110:1 to 12:1, which indicates that the algal yield probably depended on phosphorus, according to the criteria of Claesson and Forsberg (1980). A value less than 10 normally indicated nitrogen limitation, while values above 18 typically revealed phosphorus limitation. It should be noted that in some hypertrophic lakes the N:P ratio in mid-summer or early spring was lower than 10:1, which suggests that during this period the limiting element in these lakes was nitrogen. In most cases the ratio ranged from 18:1 to 12:1 in hypertrophic lakes, which shows that either N or P may be the limiting element. It was evident that P was the element controlling algal biomass in the majority of the investigated lakes.

MATERIAL AND METHODS

The data used in this paper were collected in 1978–91. The number of the lakes studied each year ranged between 18 and 44. Eighteen lakes were studied during six or nine years, sixty-one lakes during two or five years, and twenty-three lakes only during one year. In 1978–79, observations were performed three times a year: at water circulation in spring (May) and autumn (September), and at the peak of summer stagnation (July). In 1980 the lakes were sampled only in July and September. In 1980 TP was not measured, in 1979 it was measured only in May. From 1981 to 1991 the lakes were sampled on an average five (from three to eight) times during the ice-out (April or early May) through late August or early September. Water samples were collected from surface water (0.2–0.5 m).

TP was determined with the colorimetric method with ascorbic acid and ammonium molybdate used after persulphate oxidation of the sample (Reports..., 1977). Chl concentration was determined according to the method of Talling (1969). Water was filtered through Whatman GF/C filter paper. Methanol was used to extract Chl; the Chl values were calculated using Marker's equation (1972). SD was measured using a 30 cm white Secchi disk at the shady board of the boat. The data set was based on 1467 TP and 1662 Chl analyses and on 1657 SD measurements. All initial data values were transformed to their logarithms and processed by analysis of variance (ANOVA). The effects of the sampling year, observation month, and the lake concerned were taken into account as factors.

ANOVA revealed the effects of the lake for every studied lake and for every examined trophic parameter. Further, we chose one basic parameter on the scale of which we determined the value of trophy. Each lake is characterized by the value of the basic trophic parameter $X_0 = \mu_0 + x_0$, where μ_0 denotes the mean value of the basic parameter, which was calculated with ANOVA; x_0 denotes a vector whose elements are the effects of the lakes (i. e., the number of elements of the vector x_0 is only as large as the number of the lakes observed). Next, we selected supplementary trophic parameters μ_i and x_i. The parameter μ_i denotes the corresponding mean values, where $i = 1, ..., k$ (k = number of trophic parameters except the basic parameter), and x_i ($i = 1, ..., k$) are the corresponding vectors of the effects of lakes. Let $X_i = \mu_i + x_i$. Taking into account the relationship between the basic parameter and the rest of the trophic parameters by linear regression analysis, we prognosticate the values of the basic parameter for each lake:

$$X_{0i} = a_i X_i + b_i,$$

where

$$a_i = \frac{\mathrm{E}\,(X_0 X_i) - \mu_0 \mu_i}{\mathrm{E} x_i^2 - \mu_i^2} \quad \text{and} \quad b_i = \mu_0 - a_i\,\mu_i, \quad i = 0, ..., k.$$

The trophic index (T) for each lake was determined as an arithmetic mean of these prognoses:

$$T = (k+1)^{-1} \cdot \sum_{i=0}^{k} X_{0i}.$$

It is easy to understand that $\mathrm{E}T = \mu_0$.

As mentioned above, the trophic index of a lake in the present study was determined by TP, Chl, and SD. The basic parameter was TP. Regression equations were derived from the whole data base to determine the level of TP, first by Chl and then by SD. Every lake was characterized by the mean level of TP, calculated by ANOVA, during the period 1978–91; the level of TP was prognosticated first according to Chl calculated from regression, and then according to SD, also calculated from regression. The trophic index of lakes is defined as the arithmetic mean of these three parameters.

RESULTS

Table 1 presents the mean TP and Chl concentrations and SD as well as the trophic state index based on these parameters in 102 small Estonian lakes during the period 1978–91. As is evident from Table 1, the mean TP content in mesotrophic lakes varied within the range 14–23 mg P m^{-3}, the mean Chl content was 1.9–5.7 mg m^{-3}, and the mean SD 2.4–6.6 m. In eutrophic lakes the ranges of these variables were the following: 20–54 mg P m^{-3}, 4.1–21.2 mg m^{-3}, and 1.1–3.2 m; in hypertrophic lakes: TP 53–171 mg P m^{-3}, Chl 13.8–54.5 mg m^{-3}, and SD 0.5–1.7 m. Our data show that overlapping ranges indicate the real variability of these parameters in each trophic type.

A comparison of our TP, Chl, and SD data with related data in literature (Table 2) revealed the variation of TP and Chl contents in mesotrophic and eutrophic lakes to be similar to that indicated by the literature. However, the level of TP in the hypertrophic lake type is considerably higher (starting from 100 mg P m^{-3}) in Swedish lakes (Forsberg & Ryding, 1980) and in lakes of the OECD (1982) study. The Chl level, too, was higher (> 40 mg P m^{-3}) in Swedish hypertrophic lakes (Forsberg & Ryding, 1980). It should be mentioned that the Swedish lakes cited

Table 2

Total phosphorus (TP), chlorophyll *a* (Chl), and water transparency (SD) in lakes of different trophic classes

Parameter, unit	Oligo-trophic	Meso-trophic	Eu-trophic	Hyper-trophic	Reference
TP,	< 9.9	9.9–18.5	> 18.5		Dillon & Rigler, 1975
mg P m^{-3}	5–10	10–20	> 20		Wetzel, 1975
	< 15	15–30	> 30		Welch & Lindell, 1978
	< 15	15–25	25–100	> 100	Forsberg & Ryding, 1980
	< 11	11–21.7	> 21.7		Chapra & Dobson, 1981
	< 10	10–35	35–100	> 100	OECD, 1982
Chl,	0.3–2.5	1.0–15.0	5.0–140		Sakamoto, 1966
mg m^{-3}	< 4	4–10	> 10		National Academy of Sciences, 1972
	4.3	4.3–8.8	> 8.8		Dobson et al., 1974
	< 2	2–5	> 5		Dillon & Rigler, 1975
	< 3.7	3.7–10	> 10		Welch & Lindell, 1978
	< 3	3–7	7–40	> 40	Forsberg & Ryding, 1980
	< 2.9	2.9–5.6	> 5.6		Chapra & Dobson, 1981
	< 2.5	2.5–8	8–25	> 25	OECD, 1982
SD,	> 6	6–3	< 3		Vallentyne et al., 1969
m	> 5	5–2	< 2		Dillon & Rigler, 1975
	> 4	4–2.5	2.5–1.0	< 1.0	Forsberg & Ryding, 1980
	> 5	5–3	< 3		Chapra & Dobson, 1981
	> 6	6–3	3–1.5	< 1.5	OECD, 1982

were waste receiving, and thus they were heavily polluted. In the Estonian lakes studied hypertrophy becomes evident at considerably lower TP and Chl concentrations. Water transparency of SE Estonian lakes was in the same range as in the lakes presented in Table 2. Figures 1–4 show the trophic state of lakes in four counties in SE Estonia. The trophic scale is expressed in phosphorus units (mg P m^{-3}). The lakes are arranged in the order of increasing trophy. The range of the trophic scale for the lakes is from 12 to 120 mg P m^{-3}. For practical purposes we defined the boundary between different trophic levels. The transition line from mesotrophy to eutrophy on the scale is between 22–23, and from eutrophy to hypertrophy, between 47–48 mg P m^{-3}. It should be noted that strict boundaries between different trophic levels are artificial, since in real conditions there exists a continuum. Nevertheless, a quantitative classification is useful because it standardizes the approach to both defining the trophic status and the extent of cultural eutrophication. Our data showed that 22.5% of the lakes under study were mesotrophic (23 lakes), 55% eutrophic (56 lakes), and 22.5% hypertrophic (23 lakes).

Considering all three parameters, the lowest trophic status (T = 12 mg P m^{-3}) with the most transparent water, the lowest TP content, and a small Chl content was found in L. Nohipalu Valgjärv. The lowest Chl level was observed in L. Väike-Palkna (T = 14.8 mg P m^{-3}) in Võru County. The number of mesotrophic

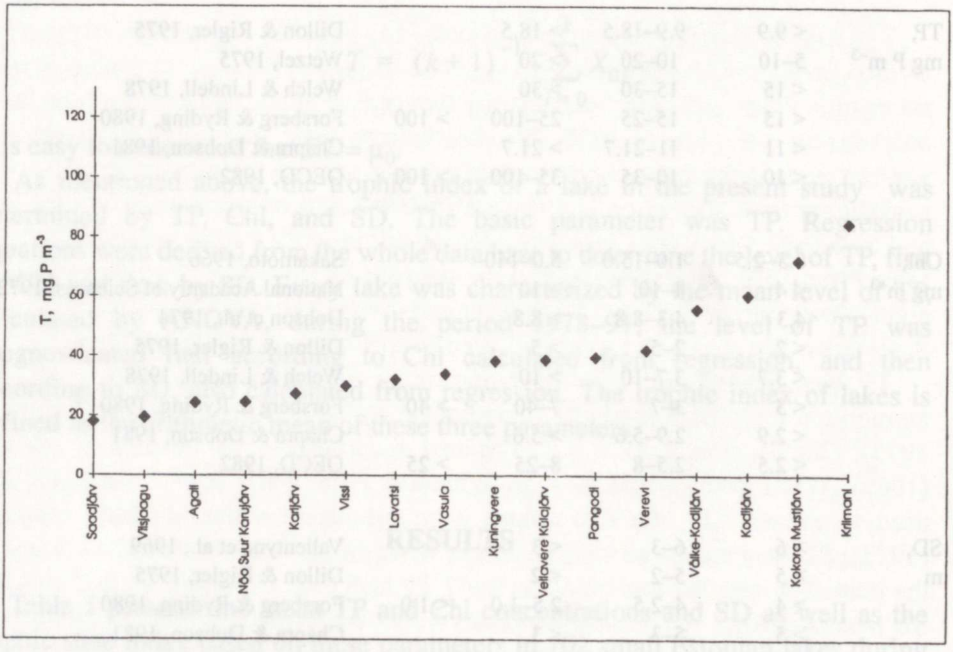

Fig. 1. Lakes of Tartu County on the trophic scale.

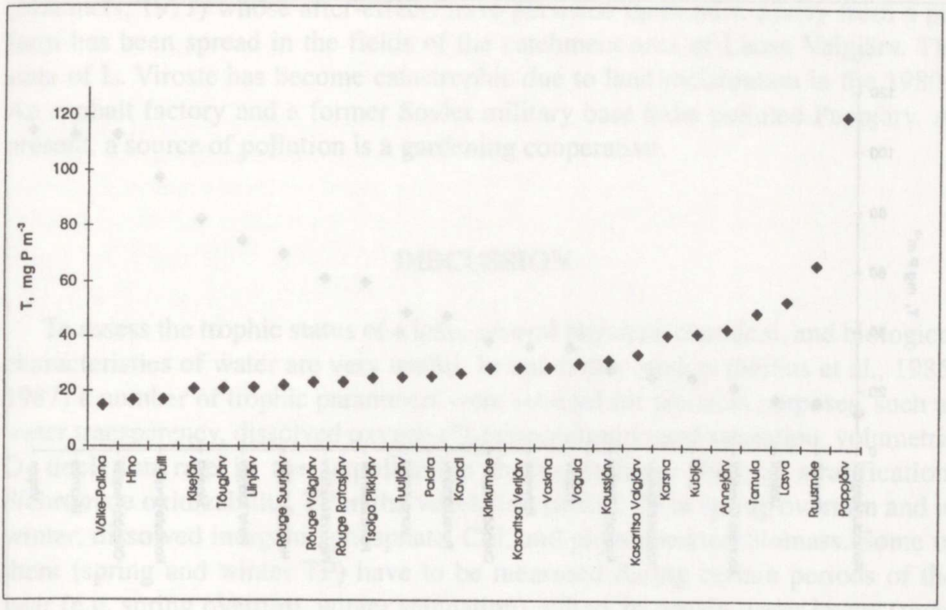

Fig. 2. Lakes of Võru County on the trophic scale.

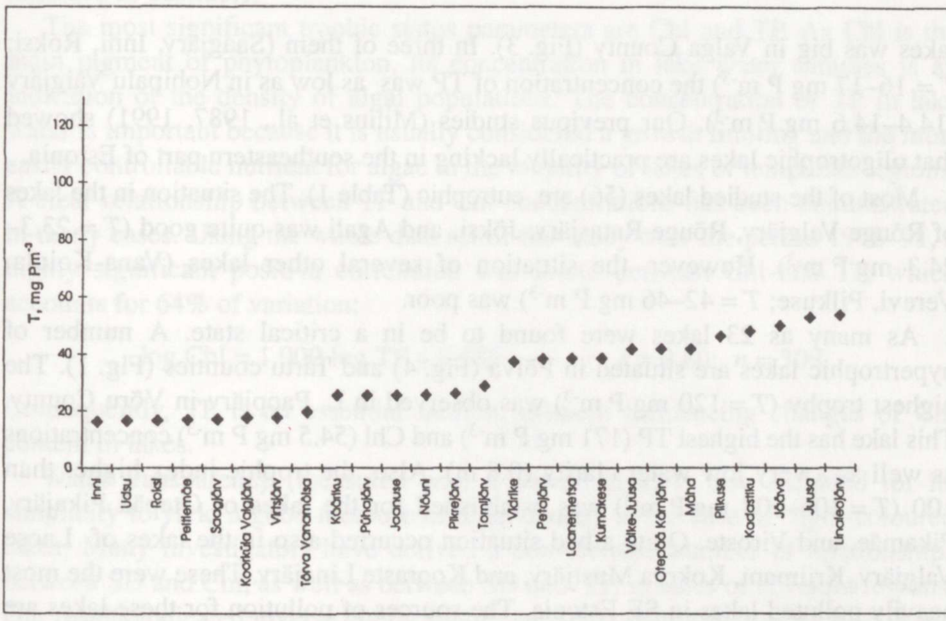

Fig. 3. Lakes of Valga County on the trophic scale.

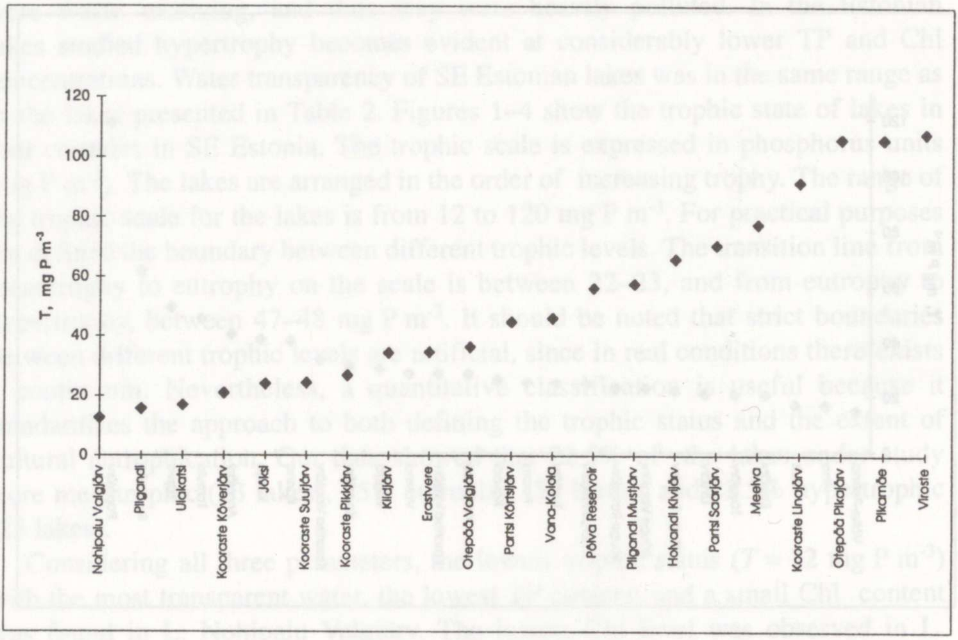

Fig. 4. Lakes of Põlva County on the trophic scale.

lakes was big in Valga County (Fig. 3). In three of them (Saagjärv, Inni, Roksi; T = 16–17 mg P m^{-3}) the concentration of TP was as low as in Nohipalu Valgjärv (14.4–14.6 mg P m^{-3}). Our previous studies (Milius et al., 1987, 1991) showed that oligotrophic lakes are practically lacking in the southeastern part of Estonia.

Most of the studied lakes (56) are eutrophic (Table 1). The situation in the lakes of Rõuge Valgjärv, Rõuge Ratasjärv, Jõksi, and Agali was quite good (T = 23.3–24.3 mg P m^{-3}). However, the situation of several other lakes (Vana-Koiola, Verevi, Pilkuse; T = 42–46 mg P m^{-3}) was poor.

As many as 23 lakes were found to be in a critical state. A number of hypertrophic lakes are situated in Põlva (Fig. 4) and Tartu counties (Fig. 1). The highest trophy (T = 120 mg P m^{-3}) was observed in L. Pappjärv in Võru County. This lake has the highest TP (171 mg P m^{-3}) and Chl (54.5 mg P m^{-3}) concentrations as well as a very low water clarity (0.8 m). Also, the trophic index higher than 100 (T = 106–108 mg P m^{-3}) was established for the lakes of Otepää Pikajärv, Pikamäe, and Viroste. Quite a bad situation occurred also in the lakes of Laose Valgjärv, Kriimani, Kokora Mustjärv, and Kooraste Linajärv. These were the most heavily polluted lakes in SE Estonia. The sources of pollution for these lakes are different. However, point pollution, especially from animal farms (Kokora Mustjärv, Kriimani) and domestic sewage (Otepää Pikajärv), plays an important role. Kooraste Linajärv has been affected by one-time intensive flax retting (Mäemets, 1977) whose after-effects have persisted up to now. Slurry from a pig farm has been spread in the fields of the catchment area of Laose Valgjärv. The state of L. Viroste has become catastrophic due to land reclamation in the 1980s. An asphalt factory and a former Soviet military base have polluted Pappjärv. At present, a source of pollution is a gardening cooperative.

DISCUSSION

To assess the trophic status of a lake, several physical, chemical, and biological characteristics of water are very useful. In our earlier studies (Milius et al., 1985, 1987) a number of trophic parameters were selected for practical purposes, such as water transparency, dissolved oxygen (O_2) concentration and saturation, volumetric O_2 depletion rate in the hypolimnion during summer thermal stratification, dichromate oxidizability, TP in the vegetation period, TP at spring overturn and in winter, dissolved inorganic phosphate, Chl, and phytoplankton biomass. Some of them (spring and winter TP) have to be measured during certain periods of the year (e.g. spring overturn, winter stagnation), others in certain water layers (most parameters in surface water, O_2 depletion rate in the hypolimnion). The simplest measured parameters are TP spring and winter concentrations. Both are based on only one, season-related measuring strategy. It should be mentioned, too, that some trophic parameters are considered important or essential, whereas others are regarded as desirable.

The most significant trophic status parameters are Chl and TP. As Chl is the main pigment of phytoplankton, its concentration in lake water samples is an indication of the density of algal populations. The concentration of TP in lake water is important because it is usually considered a growth limiting and the most easily controllable nutrient for algae in the majority of lakes of temperate regions. A clear relationship between TP and Chl concentrations has been demonstrated in many cases. Using the whole data set of this study over the period 1978–91, a highly significant positive correlation was found between Chl and TP, which accounts for 64% of variation:

$$\log \text{Chl} = 1.000 \log \text{TP} - 0.582 \qquad r = 0.80; \; n = 309$$

Consequently, TP is an essential nutrient element influencing changes of Chl content in lakes.

Water transparency (measured with a Secchi disk) is also included for its simplicity to yield a good measure of algal density in the case of light-coloured lakes. Many investigators have derived a considerable number of relationships between SD and Chl, as well as between SD and TP, in lakes of different regions. Our results indicated inverse highly significant relationships between Chl–SD and TP–SD for 102 Estonian small lakes:

$$\log Chl = 1.466 - 1.505 \log SD \qquad r = -0.87; n = 326$$
$$\log TP = 1.904 - 1.059 \log SD \qquad r = -0.76; n = 308$$

In the present study we associated the concept of trophy with these three parameters. Trophic classifications have often proved complicated due to the fact that some lakes appear mesotrophic according one criterion and eutrophic according to another. The method used in this study allows of the assessment of the trophic state of lakes by one general trophic state index based on three criteria. It should be noted that the described statistical method does not require the same trophic parameters for each lake, i.e. we can calculate the trophic state index for light-coloured lakes basing on Chl, TP, and SD; for dark-coloured lakes, on Chl and TP.

It is known that a classification of lake trophy based only on SD may be misleading in the case of dark-coloured lakes or highly turbid (non-algal) lakes. Although this study includes several dark-coloured lakes (in Põlva County), there is no need to separate SD data of dark-coloured lakes from the trophic index, because other parameters (Chl, TP) of these lakes indicate a high trophic state.

When selecting parameters for the trophic index one should consider whether the lake is dark-coloured, phosphorus or nitrogen limited. The application of an index derived from three or more parameters improves the accuracy of the assessment of the trophic state.

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VÄIKEJÄRVEDE KOLMEPARAMEETRINE TROOFSUSINDEKS

Anu MILIUS ja Henno STARAST

Troofsusindeksi väljatöötamiseks on kasutatud 102 Eesti väikejärve troofsusseisundi kompleksuuringute andmestikku aastatest 1978–1991. Järvede troofsusseisundit on iseloomustatud kolme parameetri järgi: üldfosfori ja klorofüll *a* sisaldus vees ning vee läbipaistvus. Nendest on välja valitud nn. põhiparameeter – üldfosfori sisaldus, mille skaalas on väljendatud troofsus. Uuritud järvede troofsusskaala ulatus on vahemikus 12–120 mg P m^{-3}. Vastavalt skaalale on üleminek mesotroofsest eutroofsesse tüüpi vahemikus 22–23 ja eutroofsest hüpertroofsesse 47–48 mg P m^{-3}.