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RELATIONSHIP BETWEEN WATER TRANSPARENCY AND CHLOROPHYLL *a* CONCENTRATION

Chlorophyll *a* is widely used in the estimation of phytoplankton biomass as it can be determined to a high precision and the procedure is considerably less time-consuming than the absolute determination of the phytoplankton volume. The chlorophyll *a* content is also applied as a trophic index (Carlson, 1977; Walker, 1979; Милиус, 1983; Бульон, 1985). The simplicity and reliability of the Secchi disk make it still a standard tool in limnological studies. In the bulk of earlier literature Secchi disk observations represent the only measure of water transparency. Since Secchi disk measurements give direct information about the trophic state of light-coloured lakes, it is also used as an index of the trophic state (Carlson, 1977; Walker, 1979; Милиус, 1984). Studies of lakes (Edmondson, 1972; Bachmann, Jones, 1974; Carlson, 1977; Бульон, 1977; Brezonik, 1978; Oglesby, Schaffner, 1978; Zdanowski, 1982; 1983) have demonstrated a significant hyperbolic relationship between water transparency as measured with the Secchi disk and the algal biomass as measured by chlorophyll *a* concentrations.

The hydrochemistry group of the Institute of Zoology and Botany of the Estonian Academy of Sciences has been studying chlorophyll *a* concentrations and water transparency as the parameters of the trophic state of lakes. The aim of this paper is to follow yearly changes in the chlorophyll *a* concentration and water transparency in small lakes of Estonia over the period of 13 years. We also investigate relationship between water transparency and chlorophyll *a* concentration in small lakes of Estonia and compare our regression to the equations derived from the literature data of other regions. The present study is a part of the complex investigation of the trophic state of small Estonian lakes.

Material and methods

The measurements of both the chlorophyll *a* concentration of surface waters and Secchi disk transparency on 95 small lakes of Estonia were made during 1978—1990. The lakes studied are mostly situated in South-East and South Estonia, only a few lakes being located in the eastern part of the Republic, in the Jõgeva district. The number of the lakes studied each year ranged between 18 and 44. 17 lakes were studied during

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6—9 years, 60 lakes during 2—5 years and 18 lakes only during one year. Between 1978—1979 observations were performed three times a year: in May, July and September. In 1980 the lakes were sampled only in July and September. From 1981 to 1990 the lakes were sampled 5 times on an average (range 4—8) from ice melt until late August or early September. The lakes are mostly light-coloured (water colour up to 50° on the scale of $CoSO_4$—$K_2Cr_2O_7$ standard-solutions). The methods are described in my earlier studies (Milius, 1991, 1992). The whole material includes 1568 chlorophyll *a* (hereafter chl) analyses and 1563 Secchi disk (SD) measurements during 1978—1990. In order to obtain a better survey of the data collected in various years and at different intervals, and to explain year-to-year changes in the chl concentration and SD, the initial data were processed by the analysis of variance (ANOVA) in which the logarithmic values of the initial data were used. The effect of the sampling year, the observation month and the lake were taken into account as factors. To estimate the dependence of SD on the chl concentration we applied the linear regression analysis of arithmetical mean data for each lake every year from May to August. The values of the mean data for the lakes were transformed to their logarithms.

Results and discussion

The lakes are classified according to three most essential parameters of the trophic state (total phosphorus, chlorophyll *a* and water transparency), as in our earlier papers (Milius et al., 1991; Milius, 1991). The trophic state of the lakes studied ranged from mesotrophic to hypertrophic. Our results show that 24 per cent of the lakes investigated are mesotrophic (23 lakes), 59 per cent eutrophic (56 lakes) and 17 per cent hypertrophic (16 lakes). The mean values of ANOVA and the mean ranges of chl concentrations and SD measurements grouped according to the trophic state of the lakes are presented in Table 1.

The chl content of the surface waters of the 95 lakes studied showed no one-direction changes during 1978—1990 (Fig. 1). In the course of 13 years, the chl content varied within a broad range from 5.3 to 10.8 mg/m^3. Changes in chl concentrations were fluctuating with maxima in 1978—1981 and 1987—1988, and with minima in 1984 and 1990. The mean SD values of the 95 lakes studied during the investigation period varied only slightly, from 2.0 to 2.6 m; thus, yearly changes are very small (Fig. 1). A little increase in SD was observed only in 1985 and 1986. After that visibility was stabilized at 2.1 m. Although changes in SD are relatively small, SD values are inversely related to chl concentrations. Following year-to-year changes in both parameters in Fig. 1, we can see that generally chl changes are inversely reproduced by SD values in most years (except in 1983 and 1985 when a decrease or increase of one parameter was accompanied by similar changes of the other parameter, which diminishes the significance of the hyperbolic correlation).

The yearly variation of chl and SD in meso-, eu- and hypertrophic lakes is presented in Table 2 and illustrated in Fig. 2. Undulatory changes in the chl content have been characteristic of all trophic types during the investigation period. Fig. 2 suggests that these wavy variations are inversely reflected also in SD readings, but to a considerably smaller extent. That is confirmed by a significant relationship between chl and SD during the years 1978—1990.

Table 1

Mean values and mean ranges of chlorophyll *a* concentrations and water transparency in different trophic state types

Parameter	Mesotrophic		Eutrophic		Hypertrophic	
	$\bar{x}$	range	$\bar{x}$	range	$\bar{x}$	range
chl, mg/m³	3.1	1.9—5.7	7.6	3.8—17.5	20.0	13.8—54.5
SD, m	3.6	2.8—6.6	2.1	1.4—3.1	1.3	0.8—1.7

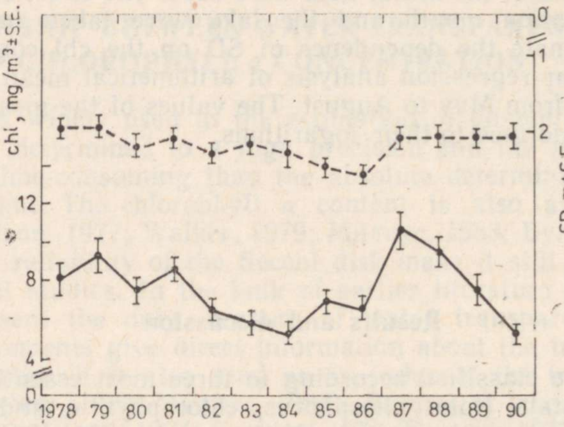

Fig. 1. Yearly changes of chlorophyll *a* concentration (—) and water transparency (- - -) in Estonian lakes during 1978—1990.

In the mesotrophic type yearly changes in chl were the smallest (2.2—4.4 mg/m³), and in SD the greatest (3—4.4 m) (Table 2, Fig. 2*a*). The smallest SD readings (3—3.1 m) were observed in the late 1970s due to the increased chl content (3.9—4.4 mg/m³) during this period. A maximum in visibility (4.4 m) was observed in 1984, when the chl content was in minimum (2.2 mg/m³). Another maximum in chl (3.6—4.3 mg/m³), causing lower transparency (3.4—3.5 m) was recorded in 1987—1988. SD maintained about the same value still in 1989, while the chl content decreased again. These changes are confirmed by a highly significant negative correlation between chl and SD ($r = -0.81$; probability level $p = 0.01$).

In the eutrophic type the chl content showed one maximum in the late 1970s and the early 1980s, followed by a gradual decline and a minimum in 1984; another, higher maximum was recorded in 1987—1988 after which the chl content decreased again (Fig. 2*b*, Table 2). Changes in SD were relatively small (1.9—2.7 m). It should be mentioned that yearly changes in the chl concentration were inversely reproduced by SD. A significant hyperbolic relationship ($r = -0.59$, $p = 0.05$) between chl and SD was observed in this trophic type during the whole study period.

The variation in the chl content was the greatest in the hypertrophic type. The chl content also changed in an undulatory mode but with maxima in 1979—1981 and 1987—1988 and with minima in 1982—1986 and 1989—1990 (Table 2, Fig. 2*c*). Contrary to chl the variation of SD was the lowest (1.0—1.6 m) in this trophic type. SD becomes insensitive to the changes of chl at higher concentrations. Although yearly changes in SD are insignificant, we notice (in Fig. 2*c*) that in most years changes in the chl content are inversely reproduced by SD. However, a few discrepancies occurred in 1986 and 1988 when an increase in the chl content brought about an increase in SD too. Due to these discrepancies the relationship between both parameters in the hypertrophic type is weaker ($r=-0.46$, $p=0.06$) than in meso- and eutrophic types.

It might be concluded that SD is more sensitive to the changes of chl at lower concentrations in mesotrophic lakes and that it becomes insensitive to the changes of chl in lakes where algal population densities are high (chl>20 mg/m^3). Studies of lakes (Bachmann, Jones, 1974) have also shown that SD of the lakes with chl values below 10 mg/m^3 are extremely sensitive to changes in algal abundance, whereas SD of the lakes with chl concentrations above this value differ to a small extent.

Many investigators have derived a considerable number of relationships between SD and the chl concentration in lakes of different regions (Table 3). From previous studies we also found a highly significant hyperbolic relationship between SD and chl for light-coloured small lakes of Estonia (Милиус, 1984; Милиус et al., 1987).

Using the whole data set of this study over the period 1978—1990, a highly significant negative correlation was found between the visibility of SD and the concentrations of chl, which accounts for 80% of variation:

$$\log SD = 0.82 - 0.50 \log chl, \qquad n=310, \quad r=-0.89, \quad p<0.0001,$$

where SD is measured in m and chl in mg/m^3.

Since literature presents now so many different SD—chl plots, it seemed useful to compare them and to determine the causes for any differences found among them.

Scattering between particular regression lines is not considerable. In Fig. 3 two regression lines (Eqs. 3 and 9 in Table 3) can be distinguished which are situated separately below the set of the other regression lines. As it becomes evident from the studies of Brezonik (1978) and Canfield and Hodgson (1983), the derivation of equations was based on the SD and chl data of dark-coloured lakes. In addition, they applied multiple regression equations with the account of an additional parameter — water colour — which accounted for 15% more variance than the regression of SD vs. chl (Canfield and Hodgson, 1983).

Thus, the above studies are not directly comparable to the others and will be excluded from further discussion. Out of the remaining 10 regression lines the Carlson equation stands out with smaller SD values in the case of larger chl concentrations (>10 mg/m^3). Contrary to the Carlson equation, the regression of Oglesby and Schaffner shows greater SD visibility at smaller chl concentrations than the remaining regression lines. However, since both authors have used, in addition to their own observation material, also written data when deriving the equations, it is difficult to pick out the causes why these regression lines differ from the remaining ones.

The remaining 8 relationships are considerably consistent. The regression lines are defined both by slopes and intercepts. The intercepts of the SD-chl regressions vary only very slightly, from 0.74 to 0.85 (Table 3), while the slopes vary a little more, from 0.39 to 0.57. Comparing these marginal curves by Forsberg and Ryding (1980) and Zdanowski (1982) in Fig. 3, we notice that the chl concentration of 1 mg/m^3 corresponds to the SD of 5.5 to 7.1 m; the chl value of 10 mg/m^3 corresponds to the SD of 1.9 to 2.2 m and the chl value of 100 mg/m^3 to the SD of 0.5 to 0.9 m.

Table 2

Mean values of chlorophyll *a* concentrations and water transparency in Estonian small lakes grouped according to trophic state

Year	Number of lakes	Number of samples		Chlorophyll mg/m³±S.E.			Water transparency m±S.E.		
		chl	SD	meso-trophic	eu-trophic	hyper-trophic	meso-trophic	eu-trophic	hyper-trophic
1978	25	83	83	3.9±0.3	8.6±0.7	14.9±4.5	3.0±0.1	2.0±0.1	1.3±0.1
1979	22	75	75	4.4±0.4	9.3±0.8	25.0±7.4	3.1±0.1	1.9±0.1	1.2±0.1
1980	21	59	61	2.9±0.3	9.3±0.9	22.6±6.2	3.7±0.1	2.0±0.1	1.4±0.1
1981	44	206	205	3.9±0.9	8.9±0.5	24.3±5.0	3.4±0.1	2.1±0.1	1.1±0.1
1982	30	152	155	2.7±0.2	7.2±0.5	17.3±3.0	3.9±0.1	2.2±0.1	1.4±0.1
1983	28	138	138	2.3±0.2	6.0±0.4	18.7±3.3	3.9±0.1	2.1±0.1	1.2±0.1
1984	18	118	129	2.2±0.2	4.7±0.4	18.5±3.6	4.4±0.1	2.4±0.1	1.1±0.1
1985	18	140	141	3.5±0.3	6.5±0.5	18.8±3.1	3.8±0.1	2.7±0.1	1.4±0.1
1986	19	93	90	2.9±0.2	6.4±0.5	20.4±3.7	3.9±0.1	2.6±0.1	1.6±0.1
1987	20	98	89	4.3±0.6	11.0±0.9	28.7±7.0	3.5±0.1	2.0±0.1	1.0±0.1
1988	20	120	118	3.6±0.5	9.9±0.7	29.4±7.2	3.4±0.1	2.0±0.1	1.4±0.1
1989	20	139	133	2.8±0.4	8.9±0.7	14.1±3.4	3.5±0.1	1.9±0.1	1.5±0.1
1990	20	120	119	2.4±0.2	5.4±0.3	14.7±3.5	3.8±0.1	2.0±0.1	1.5±0.1

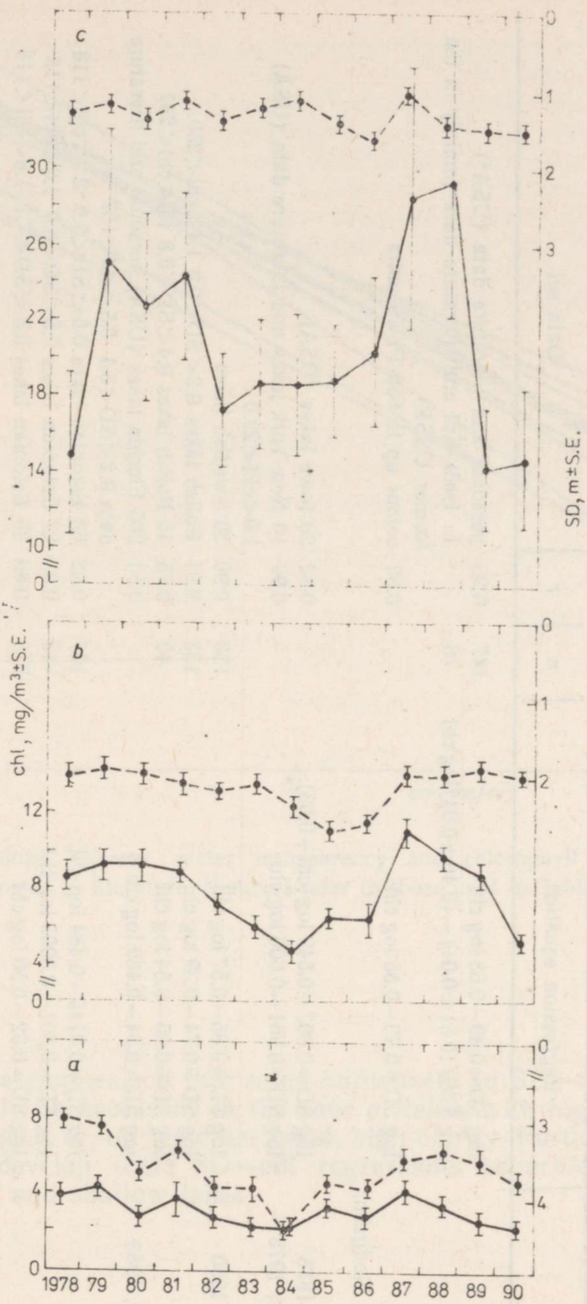

Fig. 2. Yearly changes of chlorophyll *a* concentration (—) and water transparency (- - -) in mesotrophic (*a*), eutrophic (*b*) and hypertrophic lakes (*c*).

The regressions derived from our previous papers (Eqs. 10 and 11, Table 3) are not significantly different from the one derived from the whole material studied, which indicates that the variation of SD and chl concentrations is very consistent in light-coloured lakes of South-East Estonia. It is evident that our SD—chl regressions are not significantly different from most regressions reported in literature for lakes in various countries.

Table 3

Relationships between water transparency and chlorophyll concentration reported in literature

Equation number	Reference	Regression equation	n	r	Data set
(1)	Carlson, 1977	log SD = 0.89 − 0.68 log chl	147	0.93	personal and literature data (USA*)
(2)	Бульон, 1977	log SD = (0.81 ± 0.04) − (0.46 ± 0.04) log chl	76		L. Issõk-Kul and literature data (mainly in the former USSR)
(3)	Brezonik, 1978 (cited by Canfield and Hodgson, 1983)	log SD = 0.63 − 0.55 log chl		0.82	colour up to 550 Pt-Co units
(4)	Jones and Bachmann, 1978	log SD = 0.807 − 0.549 log (chl + 0.03)		0.82	50 Iowa lakes (USA)
(5)	Oglesby and Schaffner, 1978	log SD = 0.961 − 0.606 log chl		0.92	16 New-York lakes and literature data (USA) 1.0 < chl < 29.0
(6)	Forsberg and Ryding, 1980	log SD = 0.85 − 0.57 log chl	130	0.90	30 Swedish lakes
(7)	Zdanowski, 1982	log SD = 0.74 − 0.39 log chl	153	0.91	Polish lakes 0.2 < SD < 9.0 1.4 < chl < 250
(8)	Zdanowski, 1983	log SD = 0.85 − 0.54 log chl	40	0.75	46 Polish lakes 0.4 < SD < 6,8 1.5 < chl < 237
(9)	Canfield and Hodgson, 1983	log SD = 0.54 − 0.489 log chl		0.63	205 Florida lakes (USA) personal and literature data 0.2 < SD < 8.1 0.5 < chl < 157
(10)	Милиус, 1984	log SD = 0.8145 − 0.484 log chl	107	0.92	63 Estonian lakes 0.6 < SD < 5.9 2.0 < chl < 118
(11)	Милиус et al., 1987	log SD = 0.801 − 0.5005 log chl	49	0.93	27 Estonian lakes 0.5 < SD < 5.9 1.6 < chl < 118
(2)	This study	log SD = 0.82 − 0.50 log chl	310	0.89	95 Estonian lakes 0.5 < SD < 7.1 1.6 < chl < 118

* The source of data not specified.

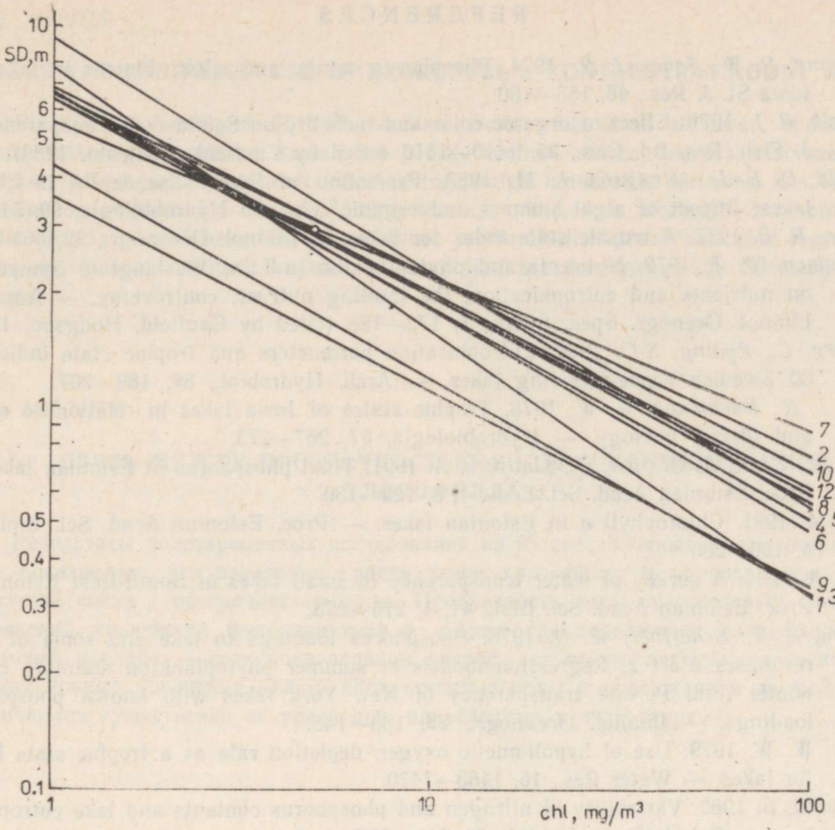

Fig. 3. Relationships between water transparency and chlorophyll *a* concentration reported in literature. Numbers refer to those used in Table 3.

It should be emphasized that some adjustment in SD—chl regressions would obviously be necessary in the case of lakes with high colour, high nonalgal turbidity, or, on the other hand, high clarity. Further work would be needed to develop these SD—chl regressions separately for highly coloured, deep and shallow lakes.

Conclusions

The long-term study of 95 light-coloured lakes in South-East Estonia suggests that yearly changes in chl concentrations are inversely reproduced by the visibility of SD. That is confirmed by a highly significant hyperbolic relationship between chl and SD during the years 1978—1990.

SD is more sensitive to the changes of chl at lower concentrations in lakes, and it becomes insensitive to the changes of chl in lakes where algal abundance is high (chl$>$20 mg/m^3).

Our SD—chl regressions are not significantly different from most regressions reported in literature for lakes in various countries.

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SEOS VEE LÄBIPAISTVUSE JA KLOROFÜLL *a* KONTSENTRATSIOONI VAHEL

Pikaajalised uuringud 95 heledaveelisel Eesti väikejärvel näitavad, et klorofüll *a* kontsentratsiooni muutused aastati on pöördvõrdelises seoses vee läbipaistvusega. Vee läbipaistvus reageerib tundlikult fütoplanktoni hulga muutustele järvedes, kus klorofüllisisaldus on väiksem kui 20 mg/m^3, ning muutub vähe, kui klorofülli kontsentratsioon ületab nimetatud väärtuse. Vee läbipaistvuse ja klorofüllisisalduse vahelised regressioonivõrrandid ei erine oluliselt kirjanduses avaldatud maade veekogudele tuletatud võrranditest.

Ану МИЛИУС

СВЯЗЬ МЕЖДУ ПРОЗРАЧНОСТЬЮ ВОДЫ И КОНЦЕНТРАЦИЕЙ ХЛОРОФИЛЛА *a*

Результаты долговременных исследований на 95 светловодных малых озерах Эстонии показывают, что изменения концентрации хлорофилла *a* по годам находятся в обратной связи с прозрачностью воды. Прозрачность воды чувствительно зависит от изменений количества фитопланктона в озерах, где содержание хлорофилла менее 20 мг/м^3, и слабо — если концентрация хлорофилла превышает указанную величину. Регрессионные уравнения между прозрачностью воды и содержанием хлорофилла не отличаются существенно от уравнений, приведенных в литературе.