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**CHLOROPHYLL – NUTRIENTS – SECCHI DISC
RELATIONSHIPS IN THE GREAT MAZURIAN LAKES
(NORTH-EASTERN POLAND)**

ABSTRACT: The relationships between SD, chlorophyll, total phosphorus and total nitrogen were analysed basing on data from 25 sites in 21 Great Mazurian Lakes collected during 12 years. Best fit for the data were reached when piecewise linear regression was used to approximate the relationship between chlorophyll and nutrient concentrations. The regression line divided the whole data set into two regions: lower, mesotrophic (chlorophyll < 20 mg m⁻³) where the response of chlorophyll to N and P was insignificant and higher, eutrophic (chlorophyll > 20 mg m⁻³) within which chlorophyll yield was proportional to nutrient increments. Except for trophic type, the relationship between chlorophyll and nutrients was affected by mixing type of lakes. No significant relationships between chlorophyll, nutrient concentrations and Secchi disc visibility were found in the shallow, polymictic lakes. Possible explanations for the observed effects including resuspension and grazing pressure on algae are proposed.

KEY WORDS: in – lake phosphorus, nitrogen, lake trophic type, mixing, chlorophyll : PP ratio, non-linear regression

1. INTRODUCTION

Since the early findings of the dependence of algal production on phosphorus in lake water (Sakamoto 1966) many models have been developed to describe the relationships between chlorophyll concentration and nutrient content. Earlier of them (Dillon and Rigler 1974, Carlson 1977) were based on

the linear relationship between chlorophyll and phosphorus (log transformed) in strict concordance with the fundamental Liebig's law of minimum. It soon, however, appeared that phosphorus or nitrogen may alternatively limit primary production, which in turn should modify simple, linear chl – TP regression models

(Smith 1982). Additionally, it has been shown that algae, could be effectively controlled by zooplankton filtrators and hence, chlorophyll yield per unit nutrient concentration can be irrelevant to the total nutrient pool. In effect, curvilinear models regressing chlorophyll on nutrient concentration has been developed (McCaughey *et al.* 1989) and/or chlorophyll – nutrient relationships has been explained by additional environmental variables like TN : TP ratio (Prairie *et al.* 1989), thermal stratification (Mazumder 1994a), grazing pattern (Mazumder 1994a, b), spring total P (Zdanowski 1982, Uchmański and Szeligiewicz 1988). Hence, within a set of lakes described by overall chl =

f(TP) regression one can find subgroups in which the response of chlorophyll to nutrient concentration varies from very steep to none (Seip and Goldstein 1994).

This study was undertaken in order: i) to check if the existing models of chlorophyll – nutrients relationships are valid for the Great Mazurian Lakes, ii) to find out if and to what extent trophic type and mixing regime of lakes can affect the relationships between chlorophyll, nutrient concentrations and water transparency and iii) to look for other possible environmental variables which might help explaining the deviations from the linear character of chl = f(nutrient) regression.

2. MATERIAL AND METHODS

Water for analyses was collected during summer from 25 sites in 21 lakes of the Great Mazurian Lakes (GML) system in north-eastern Poland (Table 1). Epilimnetic waters in the sampling sites were found to be well mixed, therefore summer samples taken up from the depth of 1 m were assumed to be representative for the whole mixed zone of lakes. Chlorophyll a (chl) was determined spectrophotometrically after acetone extraction of algae retained on Whatman GRF/C filters (Golterman 1969). Dissolved phosphorus (DP) and total phosphorus (TP) were analysed in filtered and unfiltered lake water, respectively. Particulate phosphorus (PP) was calculated as a difference TP – DP. Wet digestion of samples with concentrated perchloric acid (1 ml of acid/50 ml sample) was used for sample mineralisation. Resulting solution was analysed by the standard molybdenum blue method. Total nitrogen (TN) is

a sum of total Kjeldahl nitrogen (TKN) and nitrate-nitrogen and particulate nitrogen (PN) is a difference between the total Kjeldahl nitrogen and dissolved Kjeldahl nitrogen (DKN). TKN and DKN were analysed from unfiltered and filtered lake water, respectively, by phenate method of Solorzano (1969) after standard Kjeldahl digestion. Nitrate-nitrogen was analysed in filtered water by phenyldisulphonic method. Secchi disc depth (SD) was measured while sampling. Seston was analysed by filtering a known volume of lake water through preweighed Whatman GF/C filters and drying them to constant weight at a temperature of 105°C. Chlorophyll a, particulate and total phosphorus are expressed in mg m^{-3} , total nitrogen, particulate nitrogen and seston – in mg dm^{-3} and SD in metres throughout the text. All calculations were performed using STATISTICA software programme.

Table 1. Morphometric and trophic characteristics of the sampled lakes

Lake	Area (ha)	Max. depth (m)	Mixing type ^a	TP ^b range (µg/l)	chl a ^c range (µg/l)	Sampling period
Przystań	500	45.6	d	14–190	2–32	'84–'86, '88, '90–'96
Mamry	2004	47.0	d	35–100	3–10	'84–'86, '88, '90–'96
Dobskie			d	46–134	7–22	'84–'85, '95–'96
Świętajny	813	28.0	d	58–97	1–18	'85, '96
Dargin	3030	37.6	d	30–290	1–35	'84–'85, '91, '93–'96
Kisajno	1896	25.0	d	60–150	3–17	'84–'85, '91, '93–'94, '96
Niegocin site 1	2600	39.7	d	137–830	13–60	'84–'86, '88, '90–'96
Niegocin site 2				120–900	7–84	'84, '86, '88, '90–'96
Boczne	183	17.0	d	80–96	24–51	'84–'85, '96
Jagodne site 1	943	37.4	d	128–190	15–259	'84–'85, '91, '94, '96
Jagodne site 2				75–255	11–121	'84–'85, '91, '94
Tałtowisko	327	39.5	d	120–358	6–39	'84–'85, '91, '93, '96
Tały site 1	1162	37.5	d	66–191	35–84	'85–'86, '88, '90–'96
Tały site 2				30–175	6–81	'84–'86, '88, '90–'96
Ryńskie	620	47.0	d	50–122	26–71	'84–'86, '88, '90–'96
Mikołajskie	497	25.9	d	48–320	15–117	'86–'88, '90–'96
Beldany site 1	941	46.0	d	26–205	15–34	'86, '88, '90–'96
Beldany site 2				22–125	14–43	'84–'86, '88, '90–'95
Śniardwy	10970	23.4	p	12–170	5–29	'84–'86, '88, '90–'96
Seksty	370	6.3	p	32–140	11–42	'84–'86, '88, '90–'96
Łuknajno	680	3.0	p	34–139	3–40	'84, '86, '88, '90–'96
Tuchlin	219	4.9	p	10–67	8–59	'86, '88, '90–'96
Nidzkie	1818	23.7	d	18–150	4–23	'84–'86, '88, '90–'96
Tyrkło	236	29.1	d	35–128	18–43	'84, '86, '88, '90–'96
Białolawki	211	36.1	d	24–122	8–25	'84, '86, '88, '90–'96

^a – d = dimictic, p = polymictic

^b – TP = summer epilimnetic total phosphorus

^c – chl a = summer epilimnetic chlorophyll a

3. RESULTS AND DISCUSSION

Chlorophyll – nutrients relationships

Summer epilimnetic chlorophyll in the Great Masurian Lakes was significantly correlated with TP, although the ordinary linear regression ($\log \text{chl} =$

$0.607 + 0.376 \log \text{TP}$) explained only small part of the observed chlorophyll variability ($R^2 = 10.1\%$, $p < 0.00001$, $n = 180$). Regression line differed markedly from those presented by selected models

from literature (Fig. 1) both in slope and intercept values. Slightly higher slope was obtained when data from dimictic lakes only were taken for calculation ($\log \text{chl} = 0.554 + 0.416 \log \text{TP}$, $R^2 = 11.4\%$, $p < 0.00003$, $n = 143$) but the percentage of explained chlorophyll variability was still low. Chlorophyll in polymictic lakes was not significantly related to TP.

Zdanowski (1982), basing on a large data set of his own and literature results, presented linear regression of $\log \text{chl}$ on $\log \text{TP}$ which explained 63% of chlorophyll variability (Fig. 1). His data restricted to the Great Masurian Lakes only give, however, much weaker relationship. Zdanowski (1982) observed increasing dispersion of results with the advancement of eutrophication and generally large chlorophyll variability in lakes with $\text{TP} > 100 \mu\text{g dm}^{-3}$. This observation may partly explain low R^2 coefficient obtained in the present paper due to the increase of the trophic status which

has been noted in Masurian lakes during the last two decades (compare Table 1 below and Table II in Zdanowski (1982)).

Similarly poor relationship ($R^2 = 25\%$) between TP and chlorophyll in summer was found by Hillbricht-Ilkowska (1993a) for 25 lakes in the Suwałki Landscape Park. Hillbricht-Ilkowska (1993a) concluded that TP was a poor predictor of summer chlorophyll concentrations, which, as a rule, were lower than one would have expected from TP concentrations. This inconsistency was explained (Hillbricht-Ilkowska, 1993b, Hillbricht-Ilkowska and Wiśniewski 1993) by the poor availability of phosphorus, originating mainly from the surface runoff and combined to mineral particles. Poor summer chlorophyll response to TP concentrations was also reported for 17 lakes in the Krutynia River drainage basin (Hillbricht-Ilkowska

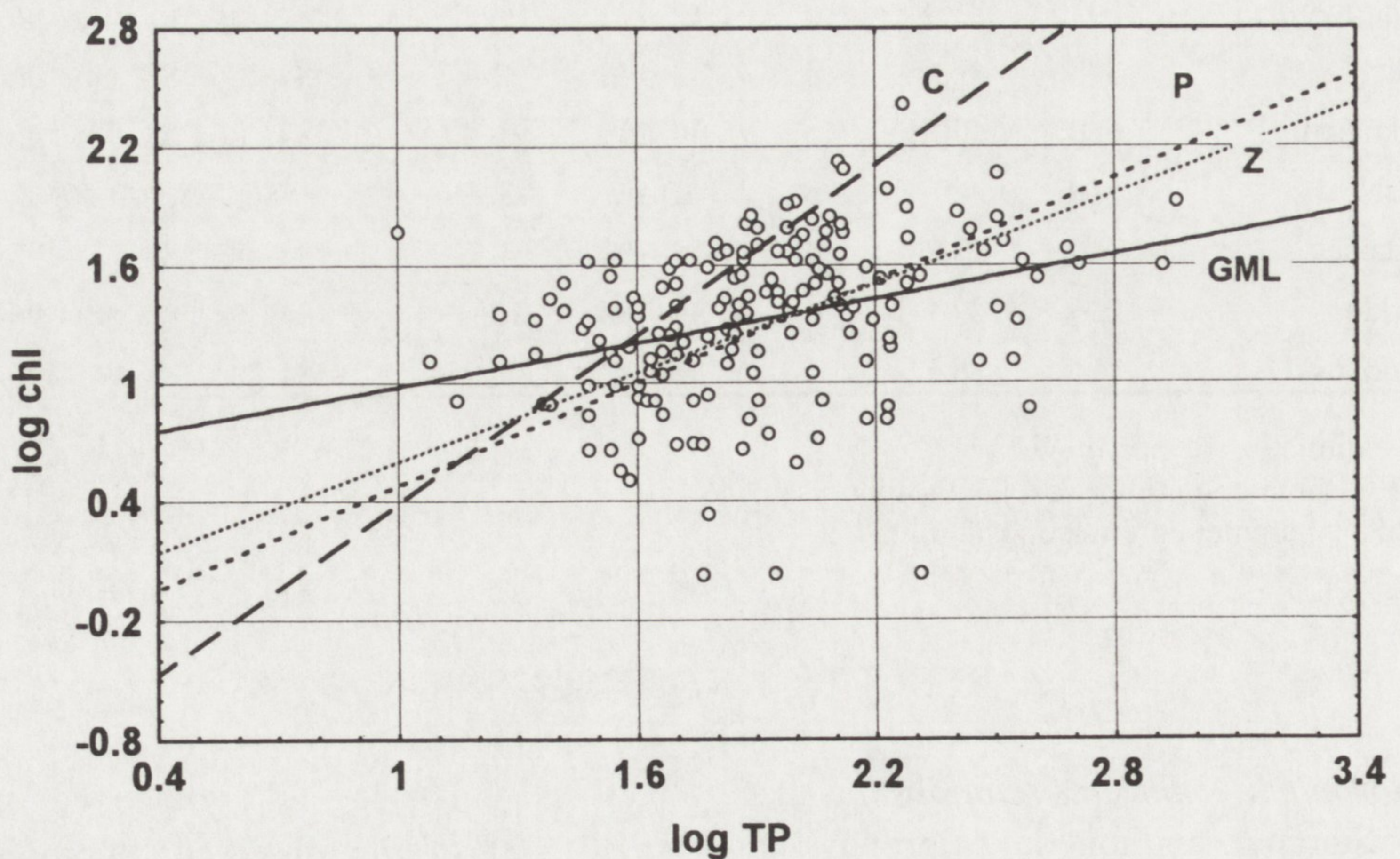


Fig. 1. Linear regression of summer chlorophyll on total phosphorus calculated for the Great Masurian Lakes (GML) compared with some examples of $\text{chl} = f(\text{TP})$ from literature (C = Carlson 1977, P = Prairie *et al.* 1989, Z = Zdanowski 1982)

et al., 1996). Chlorophyll concentrations in these lakes were again lower than those predicted from existing models of chlorophyll – TP relationships.

All these findings suggest, that chlorophyll – total phosphorus relationship may vary between lakes of different trophic type and, if so, then it can not be described by a single linear regression. To check this hypothesis, a piecewise linear regression was applied to calculate the response of chlorophyll to total phosphorus in the Great Masurian Lakes. This method describes the whole data set by the two linear approximations separated by a threshold value of the dependent variable (breakpoint), which is calculated by the programme from a given data set. This method yielded regression equation of the form $\log \text{chl} = 0.983 + 0.001 \log \text{TP}$ for $\log \text{chl} \leq 1.3243$ (which is equivalent to chlorophyll concentration 21.1 mg m^{-3}) and $\log \text{chl} = 1.227 + 0.197 \log \text{TP}$

for $\log \text{chl} > 1.3243$. Piecewise linear regression explained 64% of chlorophyll variability ($R = 0.800$) as compared with only $R = 0.319$ for the ordinary linear model. Noteworthy, the calculated breakpoint (21.1 mg m^{-3} of summer epilimnetic chlorophyll) might be roughly considered as a threshold concentration between meso- and eutrophic lakes (Chapman 1992 after various authors, OECD standards after Vollenweider, 1989). Separation of the two subsets is best visible when observed chlorophyll concentrations are plotted against those calculated from piecewise linear regression (Fig. 2). The first subset of 84 cases ($\text{chl a} \leq 21.1 \text{ mg m}^{-3}$) comprised 26 out of 37 valid data from shallow lakes. Contribution of shallow lakes does not, however, entirely explain the lack of chlorophyll response to changing TP within this group. The regression $\log \text{chl} = f(\log \text{TP})$, calculated for the remaining

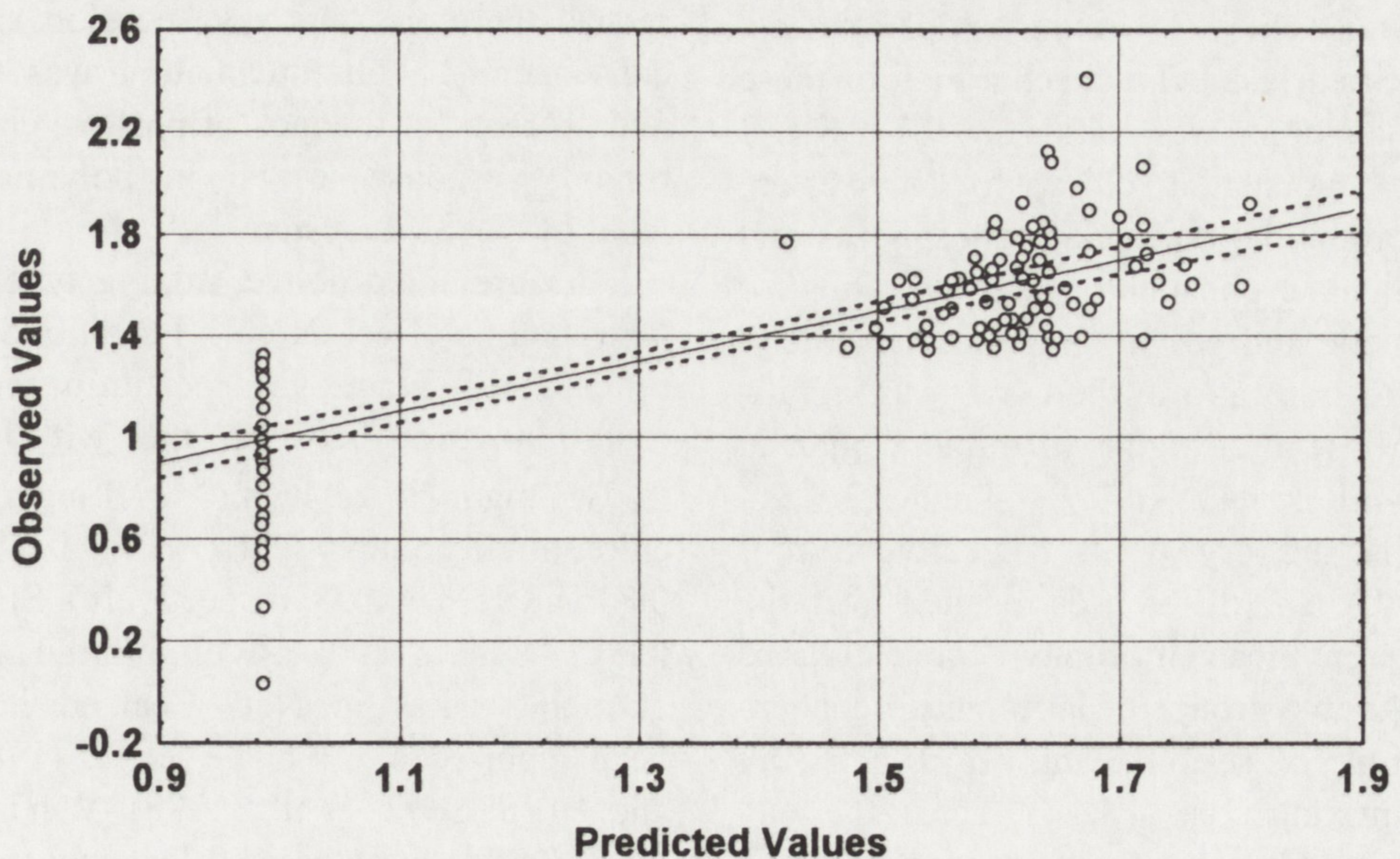


Fig. 2. Observed vs predicted (from piecewise linear regression on TP) values of log summer chlorophyll concentrations in epilimnetic waters of the Great Masurian Lakes. Data grouped vertically in the left side part of the graph represent mesotrophic lakes where no chlorophyll response to changes in TP concentration was observed

58 cases from deep, dimictic lakes of relatively low ($\leq 21.1 \text{ mg m}^{-3}$) chlorophyll content, was also statistically insignificant.

The lack of chlorophyll response to TP in shallow lakes can be attributed to the larger and irregular contribution of inorganic solids resulting from resuspension of bottom sediments (Hoyer and Jones 1983, Kristensen *et al.* 1992). It has been suggested that inorganic solids, or more generally non-algal particulate matter, may reduce chlorophyll response to TP in shallow lakes either by reducing P availability due to adsorption of phosphates (Fitzgerald 1970) or by increasing turbidity (Kristensen *et al.* 1992) and thus decreasing photosynthetic efficiency (Marzolf and Osborne 1972). There are, however, quite opposite views represented e. g. by Mazumder (1994) and Riley and Prepas (1985), who found much greater chlorophyll yield per unit increase of phosphorus in shallow lakes in contrast to weak chl – TP relationships in deep, stratified lakes. To check which of these explanations was valid for the GML I have calculated chlorophyll : seston, chlorophyll : particulate phosphorus and particulate phosphorus : seston ratios for dimictic and polymictic lakes separately. Chl/seston ratio in the GML was significantly (t-test) higher in dimictic than in polymictic lakes (4.9 ± 4.4 and $3.2 \pm 2.4 \text{ g chl mg dry wt.}^{-1}$, respectively, $p = 0.040$). The differences resulted from the different mean chlorophyll concentrations in the two groups of lakes, mean concentrations of seston being not affected by the mixing type of lakes. Thus, one may expect dilution of seston in polymictic lakes by the resuspended non-algal particulate matter, the effect similar to that described by Hoyer and Jones (1983) for reservoirs in midwestern US. No sig-

nificant differences (t-test) were found, however, in chl : PP ratio (1.36 ± 2.39 in dimictic and 1.17 ± 2.09 in polymictic) as well as in PP : seston ratio (9.62 ± 12.94 and 6.06 ± 6.16 for di- and polymictic lakes, respectively). Thus, the adsorption of P on non-algal resuspended particles (Fitzgerald 1970) seems unlikely; otherwise PP : seston should be higher in polymictic lakes. Differences in chlorophyll content of suspended seston in lakes of different mixing type coupled with the similar PP : seston ratios lead to two possible conclusions. Either algal communities in stratified lakes contained generally less particulate P to compensate for their larger contribution to seston or the non-algal particulate matter in shallow, polymictic lakes was poorer in P content. The latter alternative was true at least for one shallow lake of the GML system, namely Lake Łuknajno (Kufel and Kufel 1997), where P content in the bottom calcareous sediments was markedly lower than P in suspended seston. It seems, therefore, that resuspension and, consequently, light attenuation was the main reason for the lack of positive chlorophyll response to TP in polymictic lakes of the GML system.

As presented above, mixing type of lakes had no effect on chl : PP ratio. Significant differences in the ratio were found, however, between lakes with low ($\leq 21.1 \text{ mg m}^{-3}$) and high ($> 21.1 \text{ mg m}^{-3}$) chlorophyll content (chl : PP = 0.64 ± 0.83 and 1.94 ± 2.98 , respectively). Similar differences between oligo/meso and eutrophic lakes in New Zealand have been reported by White *et al.* (1988) and Pridmore *et al.* (1989). White *et al.* (1988) hypothesised that increased chl : PP ratio in eutrophic lakes was an effect of compensation mechanisms in algae growing under generally poorer light conditions. As an alternative explanation,

Pridmore *et al.* (1989) demonstrated that total microbial biomass in oligo/mesotrophic lakes contained up to 35% of heterotrophic organisms (bacteria and microprotozoa) while that of eutrophic lakes was dominated (in ca. 90%) by phytoplankton. Whichever the explanation is valid for the GML, it seems obvious that trophic status of lakes can affect chl : PP ratio. Consequently, one can hardly expect to describe chl – phosphorus relationships along the trophic gradient by a simple linear relationship.

In view of the Liebig's "law of minimum", one should expect strong dependence of chlorophyll on total nitrogen in the lower region of the nutrient concentrations. It was not so, however. The ordinary regression of the log-transformed data gave $\log \text{chl} = 1.213 + 0.575 \log \text{TN}$ ($R = 0.287$, $n = 172$). The relationship, though significant ($p < 0.0001$) explained only 8% of the chlorophyll variability. As for phosphorus, $\text{chl} = f(\text{TN})$ gave better approximation for dimictic lakes and insignificant relationship for shallow, polymictic basins. Piecewise linear regression produced two lines which better approximated chlorophyll – total nitrogen relationship: $\log \text{chl} = 0.930 - 0.058 \log \text{TN}$ for $\log \text{chl} \leq 1.2854$ and $\log \text{chl} = 1.550 + 0.259 \log \text{TN}$ for $\log \text{chl} > 1.2854$ ($R = 0.799$). The breakpoint dividing the two lines is equivalent to chlorophyll concentration $19.3 \text{ mg chl m}^{-3}$ which is quite close to that calculated from chlorophyll – TP non-linear regression. Again, as for phosphorus, this non-linear approximation explained 64% of chlorophyll variability and points to the lack of chlorophyll response to TN at low chlorophyll concentrations.

Other features of chlorophyll – nitrogen relationship resembled those of chl – P. The ratio of chl : PN was not affected (t-test) by the mixing type of lakes (chl :

PN = 105.39 ± 170.42 in dimictic lakes and 94.66 ± 197.52 in polymictic lakes, $t = 0.340$ $df = 193$). Significant differences in chl : PN ratio were found between the meso- and eutrophic lakes, when $\text{chl} = 21.1 \text{ mg dm}^{-3}$ was taken as a threshold value between the two types (chl : PN = 51.85 ± 56.42 and 153.08 ± 230.04 for meso- and eutrophic lakes, respectively, $t = -4.19$, $df = 193$).

The results presented above are confusing in view of the classical theory of resource limitation. Neither nitrogen nor phosphorus seems to influence epilimnetic chlorophyll in GML with chlorophyll concentration $< \text{ca. } 20 \text{ mg m}^{-3}$. At least two possible reasons could be suggested to explain these results. First is that primary production and chlorophyll maxima developed in these lakes deeper in the metalimnetic zone, not included in the present discussion. Different grazing pressure of zooplankton on algae (Mazumder 1994a, b) could also alter chl – nutrients relationships between meso- and eutrophic GML. This alternative could be proved by markedly lower chl : PP ratio in mesotrophic lakes (see above), though direct analyses of the number and biomass of zooplankters are, at present, not available.

Chlorophyll – SD relationships

Ordinary linear regression of log SD on log chl was statistically significant and explained 48.9% of SD variability ($\log \text{SD} = 0.684 - 0.392 \log \text{chl}$, $R = 0.699$, $n = 194$). This regression is quite close to that obtained by Zdanowski (1982), who calculated $\log \text{SD} = 0.74 - 0.39 \log \text{chl}$ ($R^2 = 54\%$) for summer data from 153 lakes. As expected, the regression calculated separately for dimictic lakes was more steeper and explained more of SD variability ($\log \text{SD} = 0.758 - 0.436 \log \text{chl}$, $R = 0.734$, $n = 156$) while that for

polymictic lakes was insignificant ($\log SD = 0.230 - 0.052 \log chl$, $R = 0.089$, $n = 39$) and almost parallel to the x-axis (Fig. 3).

of SD depth should be smaller in eutrophic than in mesotrophic waters. Contrary to this expectation, chl – SD regression was steeper in eutrophic lakes (Table 2).

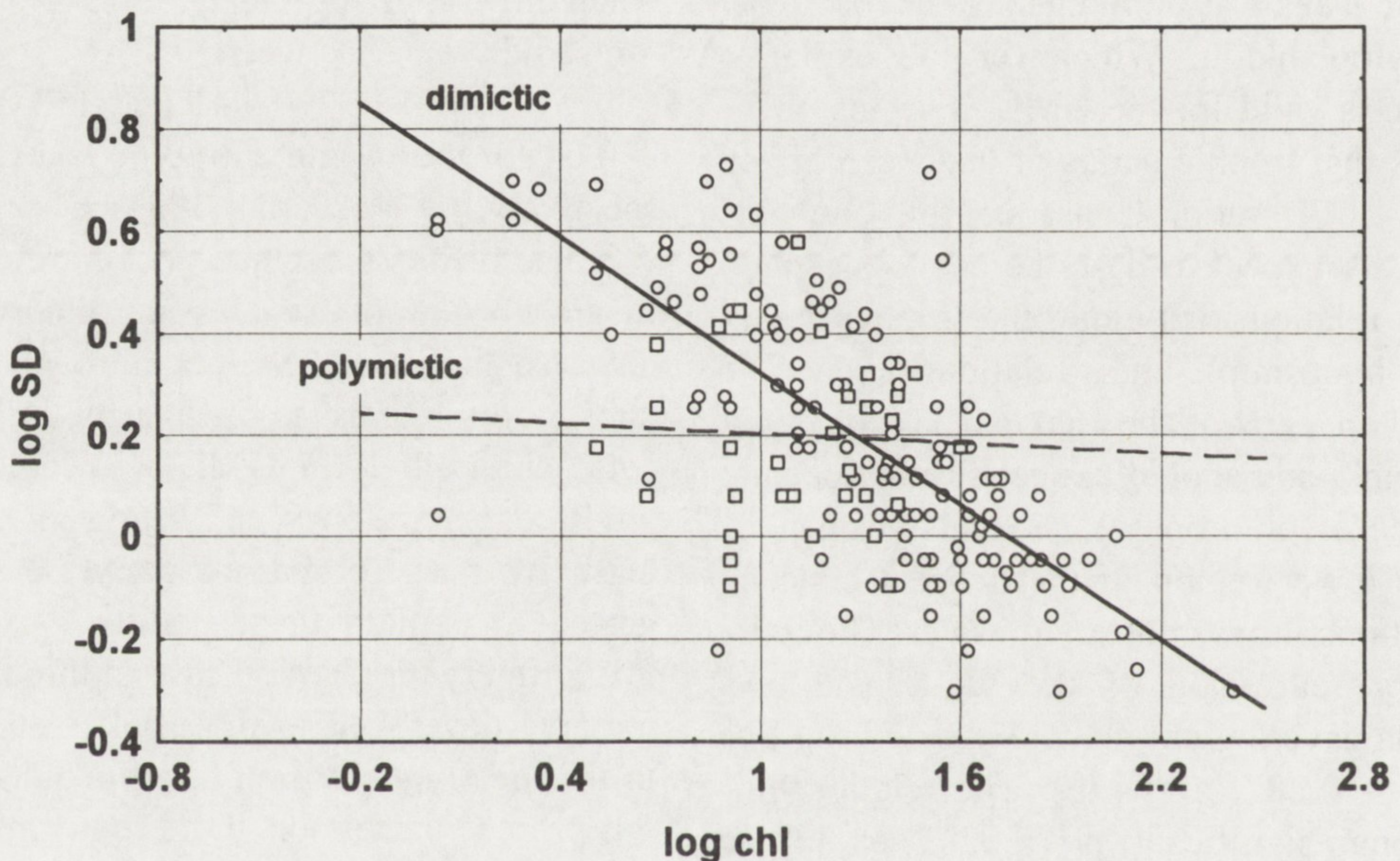


Fig. 3. The regression of Secchi disc depth on chlorophyll for dimictic (solid line, circles) and polymictic (dashed line, squares) Great Mazurian Lakes

Table 2. Coefficients of the regression $\log SD = \text{intercept} + \text{slope} \log chl$ calculated separately for meso- and eutrophic lakes in the GML system. The distinction between the two types is taken arbitrarily as that characterised by summer chl concentration ≤ 21.1 and >21.1 in meso- and eutrophic lakes, respectively

Type of lake	intercept	slope	R	n
mesotrophic (all lakes)	0.608	-0.302	0.405	97
eutrophic (all lakes)	0.698	-0.407	0.483	97
mesotrophic (dimictic only)	0.665	-0.316	0.452	69
eutrophic (dimictic only)	0.700	-0.410	0.484	87

Trophic type may affect chlorophyll – SD relationships as well. If the different distribution of algal size in oligo/meso vs. eutrophic lakes described by Pridmore *et al.* (1989) were true in the GML, then one should have expected different optical properties of water in these two types of lakes. Greater contribution of large phytoplankton in eutrophic lakes (Pridmore *et al.* 1989) means, that for a given chlorophyll increment, decrease

Unfortunately, no data on the algal size distribution in the GML are now available to check this hypothesis further. The respective parameters of regression increased slightly when polymictic lakes were excluded from calculations (Table 2). The effect of mixing type was more visible in mesotrophic than in eutrophic lakes probably due to the larger contribution of polymictic lakes to the former trophic type.

4. CONCLUSIONS

Presented data seem to confirm the thesis that chl – nutrient relationships are not linear along the trophic gradient of lakes. Piecewise linear regression which fit best to the data from GML can be considered a part of sigmoid relationship (McCauley *et al.* 1989) limited to its lower region (maximum logTP found in the GML was 2.9 while much larger McCauley's data set ranged over log TP = 4). In both data sets, however, lower range of nutrient concentrations was associated with the lack of significant positive response of chlorophyll to nutrient changes. Maximum chlorophyll response to both phosphorus and nitrogen was found in eutrophic lakes i.e. in those,

where summer chlorophyll concentration exceeded ca 20 mg m⁻³.

Mixing type of lakes was another factor affecting chl – nutrient relationships in the GML. Due to resuspension of bottom sediments, chlorophyll yield per unit TP or TN was low in polymictic lakes and the respective regressions of chlorophyll on nutrient were thus insignificant. For the same reasons, the relationships of SD and chlorophyll was poor in polymictic lakes.

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5. SUMMARY

Long-term data from 21 Great Masurian Lakes revealed poor summer chlorophyll response to both phosphorus and nitrogen increments in lake water. Ordinary linear regression of log chl on log TP explained only 10% of chlorophyll variability (Fig. 1). Exclusion of polymictic lakes improved the regression to a small extent. Distinction of two different groups of lakes with the piecewise linear regression markedly increased regression coefficient. This procedure showed a positive and significant chlorophyll response to nutrients in eutrophic lakes only (i.e. those with summer chlorophyll > ca. 20 mg dm⁻³) while in mesotrophic lakes chlorophyll did not show nutrient

dependence (Fig. 2). The two groups of lakes differed also in their summer chl : particulate phosphorus ratio (three times higher in eutrophic than in mesotrophic lakes) probably due to a compensatory mechanism developed in algae from more turbid, eutrophic waters.

The relationship between chlorophyll and Secchi disc depth was similar to those already published in the literature. The regression was sensitive to the mictic type of lakes being steep and highly significant for dimictic lakes and insignificant for polymictic ones. It appears then, that chlorophyll concentration in the Great Masurian Lakes is affected in a complex way by both the mictic type and trophic status of lake waters.

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