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# Visibility of Secchi disk in lakes of Eastern Pomerania: the role of chlorophyll *a* and turbidity

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**Abstract:** The partition of sources of total turbidity from Secchi disk (SDD) measurements according to formula: $K_T=K_W+k_c \cdot c$ in three types of Pomeranian lakes (clear, stained, turbid) was performed. Non-phytoplankton turbidity, chlorophyll *a* (Chl *a*) as well as non-algal ($K_W$) and phytoplankton ($k_c \cdot c$) extinction were regressed against total extinction coefficient ($K_T$) calculated from Secchi disk depth ($K_T$=1.7/SDD). The strong relationship between non-algal turbidity and SDD was found in all types of lakes. Linear regression between phytoplankton and SDD was statistically significant only in the group of clear and stained lakes. The limited possibility of estimating Chl *a* concentration on the basis of SDD results from the considerable diversity of the investigated lakes with respect to mineral turbidity. The light extinction due to $K_W$ ranged from 0.098 to 2.908 $m^{-1}$, and its mean value was 0.601±0.484 $m^{-1}$ and was over 2.5 times higher than the extinction due to phytoplankton. In the experiment it was demonstrated that the influence of $K_W$ on $K_T$ fluctuations can reach up to 75%, while the participation of phytoplankton does not exceed 30%. Taking into consideration the total influence of non-algal turbidity and water color, the explanation level reaches 87%.

**Key words:** Secchi disk, light extinction, turbidity, color, phytoplankton, lakes.

## Introduction

Water transparency determined by the depth of Secchi disk visibility (Secchi disk depth; SDD) is often used in limnological practice to an indirect evaluation of selected qualitative characteristics of lake wa-ter, including hydrobiological ones. The quantitative relationships between the Secchi disk visibility and the concentration of chlorophyll *a* (Chl *a*) in lake water are used for instance in aquaculture ponds for modelling the productivity of phytoplankton (Almazan, Boyd, 1978; Jamu *et al.*, 1999) or in the eva-luation of the trophic state of lake waters (Carlson, 1977). However, the underwater light regime, sha-ped by the intensity of light diffusion and absorption, is also determined by such independent factors as: the quantity of dissolved and colloidal organic matter (Schindler, 1971; Koenings, Edmundson, 1991), water turbidity caused by the presence of mineral particulates (Zettler, Carter, 1986; Koenings, Edmundson, 1991), phytoplankton concentration (Ostrofsky, Rigler, 1987), and absorption of light by water molecules (Smith, Baker, 1981). Hen-ce, relating and attributing changes of Secchi disk depth only to a single factor, especially in comparative research on lakes with different types of catchment use, hydrological type as well as economic use, and thus of heterogeneous limnic features, may lead to incorrect evaluations and decisions in the management of water resources.

This paper is an attempt to establish the dominating factor determining the Secchi disk depth (SDD) and to describe the interrelationships betwe-en the mineral and organic component of water tur-bidity in lakes in northern Poland, varying in terms of color and sources of turbidity.

## Research area

The research covered 32 postglacial lakes situated within five mesoregions of the Eastern Pomerania: Kashubian Lakeland, Bytów Lakeland, Polanów Plain, Charzykowy Plain and Drawsko Lakeland. The selected lakes constitute quite a varied set of research objects in terms of catchment, hydrological and morphological features (Tab. 1). Thus, it can be assumed that the lakes represent systems of diverse degree of hydrological relationship with their alimentation areas, different exposure and susceptibility to the supply of organic and mineral matter and different hydrodynamic conditions. The diversity of external influences as well as of intensity of internal transformations is manifested in the fact that the reservoirs represent all the classes of water quality classified according to the methods of the Institute of Environment Protection.

Table 1. Extreme and average morphometric parameters of investigated lakes: $A$ – area in ha, $Z_{MAX}$– maximum depth in m, $\overline{z}$ – mean depth in m, $V$ – volume in thousand m$^3$, $S_D$– shoreline development, σ – standard deviation

| | $A$ | $Z_{MAX}$ | $\overline{z}$ | $V$ | $S_D$ |
|---|---|---|---|---|---|
| min – max | 10.9 – 433.1 | 9.2 – 45.0 | 2.3 – 15.5 | 391.0 – 60158.7 | 1.1 – 2.9 |
| avg ± σ | 101.2 ± 113.7 | 19.3 ± 9.2 | 7.2 ± 2.7 | 8399.5 ± 13199.,8 | 1.9 ± 0.5 |

## Research methods

The measurements were performed during the years 2004 – 2005. Most of the lakes were measured four times (spring, beginning of summer, middle of summer, end of summer). Only in the case of several water bodies, the measurements were performed three times (summer), and two reservoirs were measured once. The range of the measurements used in the study covered profile measurements of chlorophyll *a* concentration (Minitracka II, Chelsea Instruments) and water turbidity (turbidity sensor YSI 6036) at one metre intervals, as well as the Secchi disk depth (SDD). Moreover, at the sites water samples were collected in order to determine the apparent color (without filtering the sample) and further detailed hydrochemical analyses.

The content of chlorophyll *a* (Chl *a*) and turbidity in the surface water layer for each measurement were assumed to be the arithmetic mean in the depth range 0 – 5 m. In the case of lakes of limited visibility of Secchi disk (smaller than 2 metres) and clearly abrupt change of Chl *a* concentration and/or water turbidity below this depth, the mean value for both parameters was determined on the basis of measurements within the depth range 0 – 2 m. The water color was determined photometrically (WTW PhotoLab Spektral)

The analysis was performed for the whole set of data (113 samples) as well as in division into three basic groups of lakes: clear, stained and turbid. Turbid lakes were assumed to be such whose turbidity expressed in nephelometric units was hig-her than 3 (NTU>3); stained lakes are such whose color expressed in the platinum scale (Hanzen number) was higher than 20 (Hz>20) and turbidity NTU <3; clear lakes were assumed to be those with NTU <2 and Hz<20. This classification is similar to the one suggested by Koenings and Edmundson (1991) with modifications of the threshold values for water color. They were modified because the determinations were performed without prior filtering the water samples, which must have shifted (increased) the threshold value of Hazen number (Hz) with respect to the determinations of the real color (filtered sample).

The depths of Secchi disk (SDD) were transformed into values of the coefficient of total light extinction ($K_T$) according to the formula by Poole and Atkins (1929), which can be treated as standard (Idso, 1982). This relationship is expressed by the following equation:

$$K_T = 1.7/SDD$$

thus a further division of the total light extinction, taking into consideration the sources causing water turbidity, was made possible. The separation of the phytoplankton and non-phytoplankton elements of extinction was performed using the following equation (Bannister, 1974; Megard *et al.*, 1980): $K_T = K_W + k_c \cdot c$,

in which $K_T$ is the total coefficient of light extinction (m$^{-1}$), $K_W$ is the fraction of the total extinction due to suspended and dissolved matter, except for phytoplankton (m$^{-1}$), $K_C \cdot c$ represents light extinction due to phytoplankton, while $Kc$ is the specific light extinction due to Chl *a* ($m^{-1}\cdot mg^{-1}\cdot m^3$) and $c$ is Chl *a* concentration ($mg\cdot m^{-3}$).

In order to establish the relationship between both forms of extinction, a coefficient of proportion of subsurface light attenuated by phytoplankton ($F$) was determined (Bannister, 1974). This is expressed by formula:

$$F = \frac{k_c \cdot c}{K_W + k_c \cdot c} = \frac{c}{(K_W / k_c) + c}$$

Light extinction by phytoplankton is the major source of turbidity when Chl *a* concentration is higher than $K_W/K_C$ ($mg\cdot m^{-3}$). This value is the threshold beyond which there is a change of the dominant factor determining the Secchi disk depth.

## Results

The initial survey of physical and biological properties of surface waters of the investigated lakes confirms their strong diversity within the group and reveals that the temporal and spatial fluctuations of SDD (0.55 – 8.10 m) may be mainly determined by a non-phytoplankton parameter (Tab. 2).

Table 2. Physical and biological characteristics of waters of investigated lakes: n – number of lakes under study, sampl. – total number of samples

| Lakes | Color (Hz) | Turbidity (NTU) | Chl *a* ($mg\cdot m^{-3}$) | Secchi disk (m) | Extinction $K_T$ ($m^{-1}$) |
|---|---|---|---|---|---|
| Clear<br>n=21 (sampl.=77) | 2.8 – 21.8<br>10.0 ± 4.0 | 0.1 – 5.7<br>1.2 ± 0.8 | 4.3 – 126.4<br>22.0 ± 22.9 | 1.35 – 8.10<br>3.50 ± 1.35 | 0.210 – 1.259<br>0.562 ± 0.233 |
| Stained<br>n=2 (sampl.=8) | 35.6 – 65.2<br>54.2 ± 9.4 | 0.7 – 6.2<br>2.3 ± 1.7 | 14.2 – 61.1<br>29.3 ± 16.6 | 1.10 – 2.50<br>1.70 ± 0.50 | 0.608 – 1.535<br>1.095 ± 0.284 |
| Turbid<br>n=9 (sampl.=28) | 6.7 – 51.4<br>23.0 ± 11.3 | 1.5 – 20.2<br>5.2 ± 4.1 | 17.2 – 155.4<br>47.3 ± 28.5 | 0.55 – 2.35<br>1.35 ± 0.55 | 0.723 – 3.091<br>1.494 ± 0.685 |
| Total<br>n=32 (sampl.=113) | 2.8 – 65.2<br>16.2 ± 13.3 | 0.1 – 20.2<br>2.3 ± 2.7 | 4.3 – 155.4<br>28.8 ± 26.2 | 0.55 – 8.10<br>2.85 ± 1.50 | 0.210 – 3.091<br>0.831 ± 0.565 |

The estimation of the specific light attenuation by phytoplankton ($K_C$) on the basis of the analysis of linear regression revealed that its values ranged from 0.0074 to 0.0137 $m^{-1}\cdot mg^{-1}\cdot m^3$ in clear and stained lakes respectively (Tab. 3). In the case of turbid lakes and with respect to the whole set of investigated lakes, there was not observed any statistically significant dependence between SDD and Chl *a* concentration, whereas the influence of turbidity was here very distinct (Tab. 3; Fig. 1). For stained and clear lakes together value $K_C$ was 0.0083 $m^{-1}\cdot mg^{-1}\cdot m^3$ with the significance of linear regression between Chl *a* and $K_T$ of $P<0.001$.

Table 3. Variation in coefficient of total light extinction ($K_T = 1.7/SDD$) explained ($r^2$) by Chl *a* concentration and turbidity (NTU) in different classes of lakes: n – number of lakes under study, sampl. – total number of samples

| Class of lakes | Chl *a* ($mg\cdot m^{-3}$) | Turbidity (NTU) |
|---|---|---|
| Clear<br>n=21 (sampl.=77) | $K_T = 0.0074\ Chl\ a + 0.3998$<br>$r^2$=0.528 | $K_T = 0.2503\ NTU + 0.2609$<br>$R^2$=0.530 |
| Stained<br>n=2 (sampl.=8) | $K_T = 0.0137\ Chl\ a + 0.6994$<br>$r^2$=0.637 | $K_T = 0.3271\ NTU + 0.5461$<br>$r^2$=0.693 |
| Turbid<br>n=9 (sampl.=28) | – | $K_T = 0.1404\ NTU + 0.7642$<br>$r^2$=0.703 |
| Clear and Stained<br>n=23 (sampl.=85) | $K_T = 0.0083\ Chl\ a + 0.4246$<br>$r^2$=0.429 | $K_T = 0.2969\ NTU + 0.2391$<br>$r^2$=0.526 |
| Total<br>n=32 (sampl.=113) | $K_T = 0.0118\ Chl\ a + 0.4919$<br>$r^2$=0.298 | $K_T = 0.1803\ NTU + 0.4200$<br>$r^2$=0.746 |
| | $K_T = 0.0076\ Chl\ a + 0.1619\ NTU + 0.2444$<br>$R^2$=0.861 | |

Moreover the determined parameters of the equation of multiple regression ($P<0.001$; $r^2 = 0.861$), that encompasses together both types of water turbidity: mineral and algal, revealed that thus calculated value $K_C$ of 0.0076 $m^{-1}\cdot mg^{-1}\cdot m^3$ was close to those above. Hence, it can be assumed that in the in-vestigated lakes of Pomerania $K_C \sim 0.008\ m^{-1}\cdot mg^{-1}\cdot m^3$ and its value is relatively constant in the group of the discussed lakes. Although, for stained lakes $K_C$ was higher but its statistical significance was smaller ($P<0.02$) and what is more, the calculations concer-ned only two reservoirs (Lake Skąpe and Lake Je-lenie Wielkie).

Assuming a constant value $K_C$ for all the lakes and mean Chl *a* concentrations in the subsurface layer of water, the value of light extinction caused by the remaining factors, mainly turbidity and water color was determined for each measurement on the basis of equation: $K_T = K_W + K_C \cdot c$

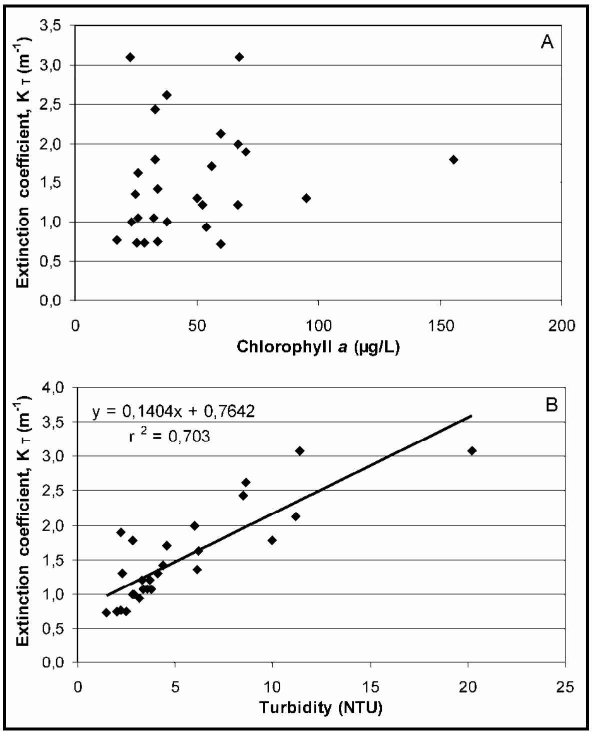


Fig. 1. Relationship between total light extinction coefficient ($K_T$) and chlorophyll *a* concentration (A) and turbidity (B) in the group of turbid lakes

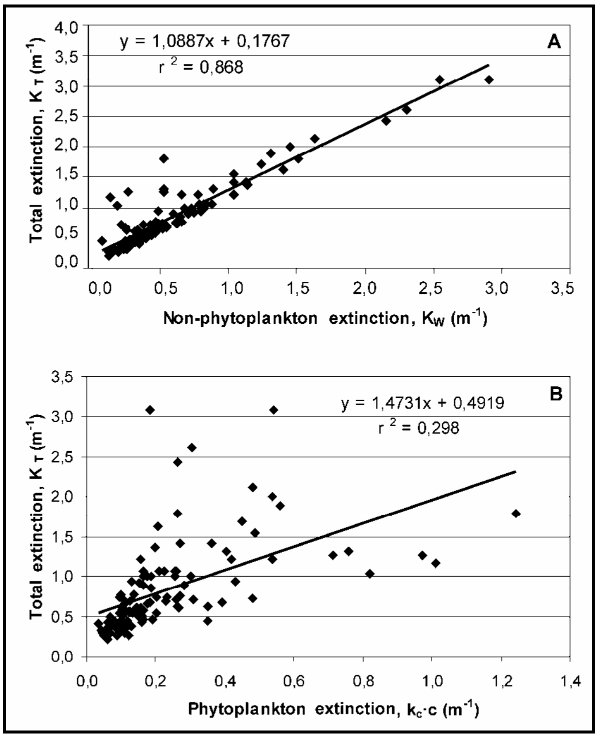


Fig. 2. Role of non-phytoplankton extinction (A) and phytoplankton extinction (B) in explaining total light extinction in Pomeranian lakes. The division into fractions was performed in compliance with formula $K_T = K_W + K_C \cdot c$, adopting value $K_C$ =0.008 $m^{-1} \cdot mg^{-1} \cdot m^3$ as mean

Figure 2a presents the linear regression between $K_W$ and total extinction coefficient ($K_T$). This relationship, significant at level P<0.001, proves that the dominant factor conditioning SDD variation is turbidity ($r^2$=0.868). Deviations of few points from the straight line of regression correspond to spring measurements performed in lakes of a high chlorophyll concentration, whose values ranged from 89.1 to 155.4 $mg \cdot m^{-3}$. A similar relationship determined between the extinction due to Chl *a* and total light extinction (Fig. 2b) does not reveal such a clear de-pendence ($r^2$=0.298).

Using the specific light extinction coefficient due to turbidity ($K_W$ = 0.160), calculated in the equation of multiple regression (Tab. 3), assuming that it is constant in all the lakes, the fraction of total extinction caused by water turbidity was simultaneously distinguished by means of formula $K_T = K_C + K_W \cdot w$ where $w$ is turbidity expressed in NTU, and $K_C$ is light extinction by Chl *a* and water color. This time also a strong statistical dependence was obtained between $K_T$ and $K_W$ and a less significant relation between $K_T$ and $K_C$ (Fig. 3).

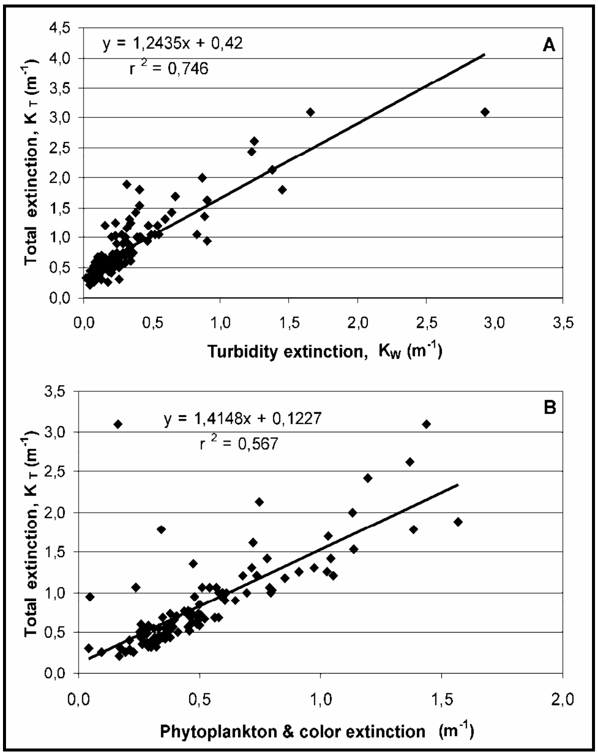


Fig. 3. Role of extinction due to water turbidity (A) and both phytoplankton and water color (B) in explanation of total light extinction in Pomeranian lakes. The division into fractions was performed in compliance with formula $K_T = K_C + k_W \cdot w$, adopting value $k_W = 0.160\ \mathrm{m^{-1} \cdot NTU^{-1}}$ as mean

## Discussion

The values of $K_C$ determined on the basis of the analysis of linear regressions for the lakes of Eastern Pomerania ranged between 0.0074 and 0.0137 $\mathrm{m^{-1} \cdot mg^{-1} \cdot m^3}$. Higher values were recorded in relationships of a smaller statistical significance (lakes in total) or in classes of lakes with a small number of samples (stained lakes). Coefficient $k_c$ = 0.008 $\mathrm{m^{-1} \cdot mg^{-1} \cdot m^3}$ was assumed to be representative of the investigated group of lakes. In comparison to the va-lues given for other lakes of the temperate and tropical zones (Bannister, 1974; Bindloss, 1974; Megard *et al.*, 1980; Jamu *et al.*, 1999) it appeared to have one of the smallest values and to be close to the one observed in Loch Leven (Bindloss, 1974) and in fish ponds of Thailand and Panama (Jamu et al., 1999), where it was 0.009-0.010 $\mathrm{m^{-1} \cdot mg^{-1} \cdot m^3}$. The range of light extinction by phytoplankton ($k_c \cdot c$) in the investigated lakes ranged from 0.035 to 1.243 $\mathrm{m^{-1}}$, assuming the mean value of 0.230 ± 0.209 $\mathrm{m^{-1}}$.

The determination of the proportion (F) of light extinction by phytoplankton reveals that its arithmetic mean for the whole group is just 28.1%, and only in few cases its value exceeds 50% (Fig. 4). The ca-ses of domination of extinction due to phytoplankton over the remaining fractions were observed al-most only in spring with a high chlorophyll concentration over 43.7 $\mathrm{mg \cdot m^{-3}}$.

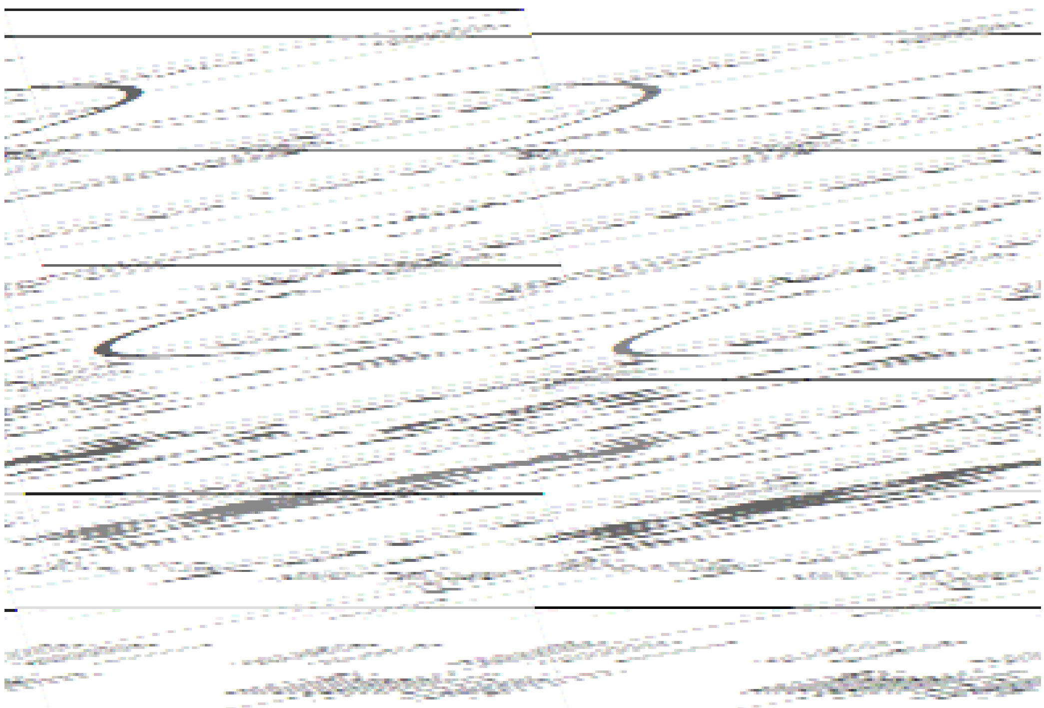

Fig. 4. Proportion of light extinction by phytoplankton (F) in Pomeranian lakes for different Chl *a* concentrations. White circles stand for cases in which the influence of Chl *a* on the total extinction coefficient was dominating in comparison with the remaining attenuating factors. The vertical line denotes Chl *a* concentration (43,7 $mg^1 \cdot m^{-3}$) above which its role as the dominant source becomes distinct

The limited possibility of estimating Chl *a* concentration on the basis of SDD measurements results from the considerable diversity of the investigated lakes with respect to non-algal turbidity (Fig. 5). The light extinction caused by non-algal turbidity ($K_W$) ranged from 0.098 to 2.908 $m^{-1}$, and its mean value was 0.601 ± 0.484 $m^{-1}$ and was over 2.5 times hig-her than the extinction due to phytoplankton. With low Chl *a* concentrations, the dominating factor de-termining SDD becomes non-phytoplankton turbi-dity, which is clearly presented in figure 5. This is an observation compliant with the theoretical considerations made previously by Lorenzen (1980), Megaard *et al*. (1980), confirmed also by experimental research by Elser (1987), Koenings and Ed-mundson (1991) or Jamu *et al*. (1999). The influence of turbidity and/or the content of yellow substances (water color) can explain the variability of SDD or $K_T$ even in 70 – 90%.

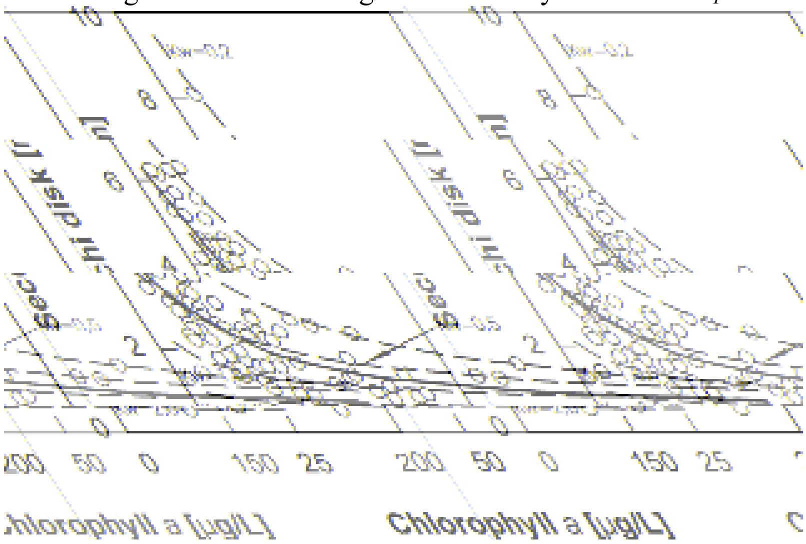

Fig. 5. Role of non-phytoplankton turbidity in establishing relationships between Secchi disk visibility (SDD) and Chl *a* concentration. Broken lines denote the dependence between SDD and Chl *a* for different values of *Kw*. These curves were drawn assuming that 20% of surface radiation reaches SDD. Solid line denotes the dependence between SDD and Chl *a* for the whole group of investigated lakes

In the experiment it was demonstrated that the influence of non-algal turbidity on fluctuations of $K_T$ can reach up to 75%, while the participation of phytoplankton does not exceed 30% (Fig. 2 – 3). Ta-king into consideration the total influence of non-phytoplankton turbidity and color, the explanation level reaches 87% (Fig. 2). This research confirmed also the fact that the use of SDD observations to de-termine the trophic state index for lakes (Trophic State Index by Carlson) has a very limited range of applicability. This is also confirmed by practical attempts at determining it undertaken by Borowiak and Lange (2005) for lakes situated in the catchment of the upper Radunia River. The differences between TSI determined on the basis of SDD measurements and Chl *a* concentration and/or total phosphorus (TP) reached several tens per cent.

## Acknowledgement

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## Streszczenie

Przezroczystość wody określana głębokością widzialności krążka Secchiego (SDD) w praktyce limnologicznej wykorzystywana bywa często do pośredniej oceny wybranych charakterystyk jakościowych wody. Podwodny reżim światła uwarunkowany jest jednak wieloma niezależnymi czynnikami, toteż wiązanie zmian widzialności krążka Secchiego wyłącznie do jednego z nich, szczególnie w badaniach porównawczych, może prowadzić do błędnych ocen i opartych na nich decyzji w zakresie gospodarowania zasobami wodnymi. W pracy niniejszej podjęto próbę ustalenia dominującego czynnika determinującego głębokość widzialności krążka Secchiego oraz opisania wzajemnych relacji pomiędzy mineralną oraz organiczną składową mętności wody w 32 jeziorach Pomorza Wschodniego zróżnicowanych pod względem zlewniowym, hydrologicznym oraz morfologicznym (tab. 1). Wpływ poszczególnych składowych mętności na wody na warunki przenikania światła ustalono poprzez podział całkowitej ekstynkcji na jej składową fitoplanktonową ($K_C$) oraz niefitoplanktonową ($K_W$), zgodnie z równaniem $K_T = K_w + k_c \cdot c$, oraz wyznaczając wskaźnik proporcji (F) osłabiania oświetlenia powierzchniowego przez chlorofil (Chl *a*).

Rozpoznanie fizycznych i biologicznych cech wód badanych jezior wskazuje na ich silne międzygrupowe zróżnicowanie i pokazuje, że czasowo-przestrzenne wahania SDD (0,55 – 8,10 m) i współczynnika ekstynkcji ($K_T$; 0,210 – 3,091 $m^{-1}$) są silnie zdeterminowane zmąceniem wywołanym przez materię mineralną (tab. 2, 3). W jeziorach o dużym zmąceniu mineralnym jak też w całej analizowanej zbiorowości jezior nie stwierdzono istotnej statystycznie zależności pomiędzy SDD lub $K_T$ a koncentracją chlorofilu *a* (tab. 3, ryc. 1). Bardziej wyraźny wpływ czynników niefitoplanktonowych zauważalny jest przy podziale ekstynkcji całkowitej ($K_T$) na składowe $K_C$ oraz $K_W$, przyjmując stałą wartość $k_c \sim 0{,}008\ m^{-1}\cdot mg^{-1}\cdot m^3$ dla wszystkich jezior (ryc. 2). Tym razem siła związku statystycznego jest jeszcze większa ($P<0{,}001$; $r^2=0{,}868$). Podobne zależności uzyskano dokonując podziału $K_T$ przy założeniu, iż $k_w \sim 0{,}160\ m^{-1}\cdot NTU^{-1}$ (ryc. 3). Ustalając proporcję (F) osłabiania światła przez fitoplankton okazuje się, że jej średnia wartość wyniosła zaledwie 28,1%, a tylko w nielicznych przypadkach okresu wiosennego, gdy koncentracja chlorofilu przekraczała 43,7 $mg\cdot m^{-3}$, jej wartość przekracza 50% (ryc. 4).

Ograniczona możliwość szacowania koncentracji Chl *a* na bazie pomiarów SDD wynika ze znacznego zróżnicowania badanych jezior pod względem mętności wywołanej obecnością substancji mineralnych (ryc. 5). Ekstynkcja światła powodowana mętnością ($K_W$) wahała się w granicach 0,098 – 2,908 $m^{-1}$, a jej wartość średnia wyniosła 0,601 ±0,484 $m^{-1}$ i była ponad 2,5 razy większa od osłabiania przez fitoplankton. Przy niskich koncentracjach Chl *a* dominującym czynnikiem kształtującym SDD staje się mętność niefitoplanktonowa, co doskonale ilustruje rycina 5. Wpływ mętności i/lub zawartości substancji żółtych może aż w 70 – 90% wyjaśniać zmienność SDD lub $K_T$.