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Light conditions in Lake Zurich 1979–1981
Part I: Secchi disk transparency[1]

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In Lake Zurich weekly measurements of Secchi disk transparency were made over a period of three years, from 1979–1981. Simultaneously the light intensity and the dry weight of suspended matter were determined at several depths from the surface down to 20 metres. Periodically chlorophyll *a* concentrations were also measured.

Based on all available data, five periods with similar properties of transparency can be distinguished during the year. The daily oscillations of light energy have only a moderate influence on the transparency. At a Secchi disk depth of 2 metres 22% of the subsurface light intensity was measured, at 12 metres 3%. The exponential decrease found is a result of the decrease in the concentration of suspended particles which gives rise to less intense occultation and light scattering. An exponential relationship between transparency and total extinction coefficient was found. Based on the data presented in this paper, a theoretical maximum in the Secchi disk transparency was estimated to be 25 metres.

Lichtverhältnisse im Zürichsee 1979–1981
Teil I: Durchsichtigkeit nach Secchi

In der dreijährigen Periode von 1979 bis 1981 wurde im Zürichsee wöchentlich die Durchsichtigkeit nach Secchi gemessen. Gleichzeitig bestimmten wir in verschiedenen Tiefen von der Oberfläche bis 20 Meter die Lichtverhältnisse sowie das Trockengewicht der suspendierten Stoffe. Periodisch wurde die Chlorophyll *a* Konzentration ermittelt.

Bei der Betrachtung aller vorhandenen Durchsichtigkeitswerte liessen sich innerhalb eines Jahres fünf Perioden mit ähnlichen Eigenschaften unterscheiden. Die täglichen Schwankungen der Lichtintensität beeinflussen die Durchsichtigkeit nur geringfügig. In einer Secchi-Tiefe von 2 Meter massen wir 22% der Lichtintensität unmittelbar unter der Oberfläche, in 12 Meter waren es 3%. Die gefundene exponentielle Abnahme ist hauptsächlich bedingt durch verminderte Konzentrationen an suspendierten Partikeln: Die Folge davon sind geringere Okkultation und Lichtstreuung. Es wurde ein exponentieller Zusammenhang zwischen Durchsichtigkeit und dem vertikalen Extinktionskoeffizienten festgestellt. Mit Hilfe der vorhandenen Daten konnte eine theoretische maximale Durchsichtigkeit von 25 Metern geschätzt werden.

1 Introduction

The procedure by which the Secchi disk transparency is determined is simple: a white disk (usually 30 cm in diameter) is let down from the surface until it just disappears from view. The observations must be made through a shaded area of water surface. It is common to determine the point of disappearance as the disk is lowered, allow it to drop a little farther, and then determine the point of reappearance as the disk is raised. The mean of the two readings is taken as the Secchi disk transparency (E. Hutchinson 1957). The technique was developed in the last century by A. Secchi (1866). F. A. Forel (1901) car-

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ried out comprehensive investigations of the optical properties of Lake Geneva and Lake Constance. His theoretical considerations were taken into account in the fundamental work by F. Sauberer und F. Ruttner (1941), and some of his ideas are also discussed by W. T. Edmondson (1980). On the other hand formerly important and commonly accepted facts are neglected by several authors who have lately published papers on Secchi disk relationships (J. E. Tyler 1968; R. E. Carlson 1977, 1980).

Although there are a set of factors influencing Secchi disk transparency, several important relationships have already been determined:

- In the English Channel H. H. Poole and W. R. G. Atkins (1928) found that the ratio (1.7/K) is equal to the Secchi disk transparency (K = vertical extinction coefficient).
- J. J. Graham (1966) found excellent agreement between Secchi disk transparency and extinction coefficient in the central and eastern North Pacific Ocean.
- In highly productive lakes Secchi disk transparency values are related to primary production, but the correlation decreases with increasing transparency (R. A. Vollenweider 1960).

The aim of my investigations was to estimate the value of Secchi disk transparency measurements in characterizing the light conditions in Lake Zurich.

2 Material and Methods

I used a white Secchi disk of 30 cm diameter. The determinations were carried out as described in Chapter 1, about 200 metres offshore from the Limnological Station at Kilchberg. Reflection was eliminated by using a bathyscope. The light measurements were normally made between 11 a.m. and 2 p.m., from 0.05 to 20 metres depth at 1 metre intervals. The instrument used was a Li-Cor Li-185 with sensor Li-192S (Li-Cor, Inc., Lincoln, Nebraska, U.S.A.). The method of least squares (L. Sachs 1974) was used to fit a straight line through the natural logarithm of the light data. For the calculations only the measurements from 0.05 metres to the Secchi depth were included. I calculated stepwise regressions (Chapter 4) and nonlinear regressions (Fig. 3, 4, 5) by means of BMDP-77 programs (W. J. Dixon and M. B. Brown 1977). The jobs were run on the University of Zurich computer (IBM system 3033). Data on suspended matter was obtained from the monthly plankton counts carried out by the City of Zurich Water Supply (unpublished data). To determine the

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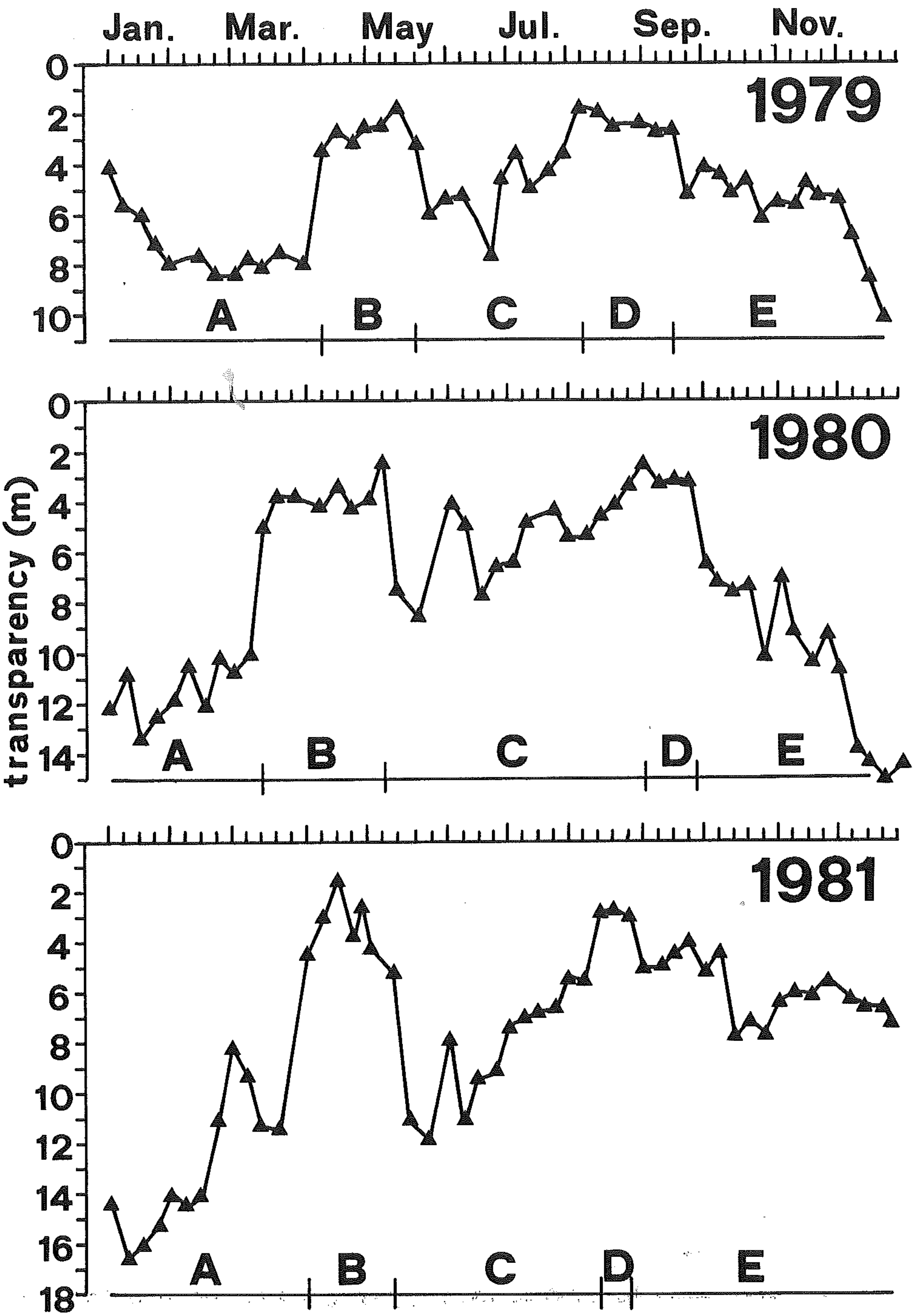
▶ Fig. 1. Weekly measurements of Secchi disk transparency in 1979, 1980 and 1981. A, B, C, D, E: Five periods with similar properties (for details see text).

Bild 1. Verlauf der wöchentlich gemessenen Durchsichtigkeitswerte nach Secchi in den Jahren 1979, 1980 und 1981. A, B, C, D, E: Fünf Perioden mit ähnlichen Eigenschaften (Einzelheiten im Text).


Jan.
Mar.
May
Jul.
Sep.
Nov.
1979
1980
1981
transparency (m)
0
2
4
6
8
10
12
14
16
18
A
B
C
D
E

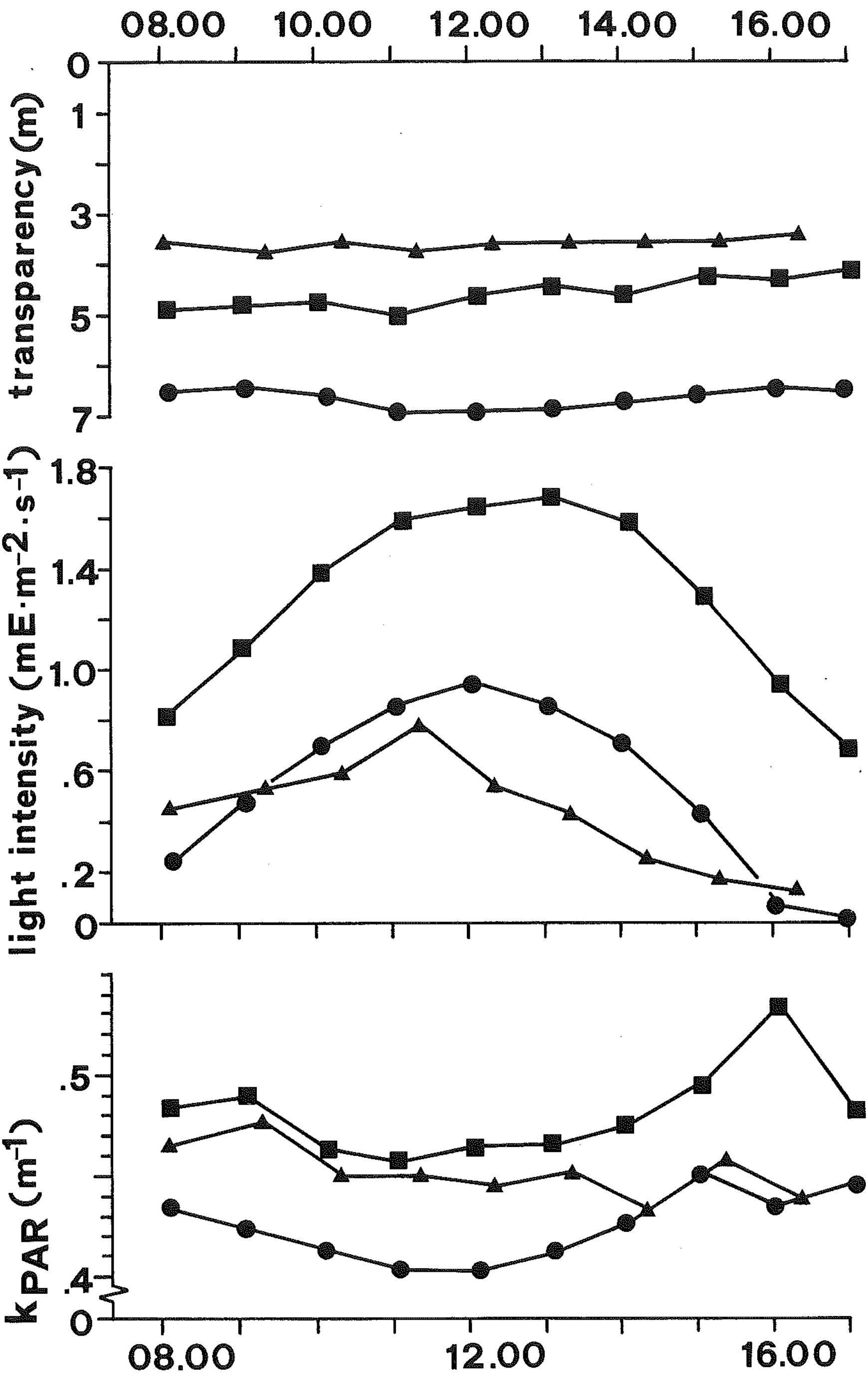
dry weight of suspended matter 2 litres of Lake Zurich water were filtered through GF 92 filters (Schleicher & Schuell AG, Feldbach, Switzerland) and dried at 110 °C. The loss of filter substances washed out by filtration was corrected for by adding 0.4 mg · l^{-1} to the final results. The chlorophyll *a* content of the water was determined by a fluorometric method (F. Schanz 1982).

3 Data from the period 1979–1981

Secchi disk transparency has been measured in Lake Zurich since 1897 but not continuously. Usually one determination per month was carried out. The results are presented by E. A. Thomas (1971) and F. Schanz und E. A. Thomas (1980) mainly in relationship to lake restoration. In 1979 we started making weekly measurements of transparency near the Limnological Station at Kilchberg. The results are given in Fig. 1. Periodical fluctuations of the values are obvious: Five periods (A–E) can be distinguished. Period A: In the months January, February and March occurred the highest transparency values of the year. In 1979 increasing values were measured in January as a result of decreasing amounts of *Aphanizomenon flos-aquae.* In January 1981 the water was extremely clear; the Secchi disk disappeared in a depth of about 16 metres. A similar good transparency was last recorded in January 1897 by A. Pfenninger (1902). In February 1981 the mass development of *Stephanodiscus hantzschii* caused a temporary loss in transparency. Period B: In March or at the beginning of April the transparency diminished to a mean of 2 to 4 metres for a period of 7 to 8 weeks. In all three years observed, period B starts with a rapid turbidity increase in one week. This appears to be mainly due to mass developments of flagellates (species of *Cryptomonas* and *Rhodomonas*) and diatoms *(Fragilaria crotonensis, Stephanodiscus hantzschii).* Period C: All of a sudden the high density of phytoplankton disappeared because of zooplankton grazing, and the Secchi disk transparency increased to 6–8 metres in 1979 (for 4 weeks) and 1980 (for 2 weeks) to about 12 metres in 1981 (for 2 weeks). In summer (June, July and part of August) decreasing transparency was measured. The oscillations observed in 1980 and 1981 did not occur markedly in 1979. To determine a periodicity more annual series are needed. Period D: The second annual minimum occurs at the end of summer or at the beginning of autumn. At that time the water is found to contain a lot of white particles and the lowest conductivity values of the year are measured: $CaCO_3$ precipi-

▶ Fig. 2. Variations in transparency, surface light intensity and vertical extinction coefficient of photosynthetically active radiation (k_{PAR}) on three different days. ■ 21. 8. 1980; ▲ 27. 8. 1980; ● 2. 11. 1981.

Bild 2. Verlauf von Durchsichtigkeit, Überwasser-Lichtintensität und vertikalem Extinktionskoeffizienten (k_{PAR}) an drei verschiedenen Tagen. ■ 21. 8. 1980; ▲ 27. 8. 1980; ● 2. 11. 1981.


08.00
10.00
12.00
14.00
16.00
transparency (m)
0
1
3
5
7
light intensity (mE·m⁻²·s⁻¹)
1.8
1.4
1.0
.6
.2
0
KPAR (m⁻¹)
.5
.4
0
08.00
12.00
16.00

tates due to high pH values caused by a high biological activity, a phenomenon described in detail by L. Minder (1943). Period E: The light intensity decreases markedly and also the length of the day. This decrease in light energy causes a decrease in phytoplankton and as a consequence an increase in transparency.

4 Daily variation of Secchi disk transparency

According to the work of O. v. Aufsess (1903) the depth of disappearance of the Secchi disk is independent of the incident light energy. This supposition was further checked by B. Åberg und W. Rodhe (1942). Their measurements confirmed the results of O. v. Aufsess; but at sunset the Secchi disk transparency was found to decrease markedly.

On three days measurements were made of Secchi disk transparency and light intensity at hourly intervals; further the vertical extinction coefficients of photosynthetically active radiation k_{PAR} were calculated. I was interested in the fluctuations of these parameters and in their relationships. The results are presented in Fig. 2. Only small variations in transparency could be observed (21. 8. 1980: minimum 4.15 m, maximum 5.0 m; 27. 8. 1980: min. 3.4 m, max. 3.7 m; 2. 11. 1981: min. 6.4 m, max. 6.9 m). The surface light intensity curves show clearly that the weather was sunny on 21. 8. 1980 and 2. 11. 1981 and cloudy on 27. 8. 1980. On the two sunny days the k_{PAR}-values were lower at midday than in the morning or in the evening, mainly due to the shorter light path at high sun elevation. The influence of phyto- and zooplankton migration on k_{PAR} will have to be investigated separately.

Further I tested the influence of surface light intensity and vertical extinction coefficient on Secchi disk transparency. By means of stepwise regression I found that on 21. 8. 1980 neither surface light intensity nor vertical extinction coefficient had any influence on transparency; but six days later (27. 8. 1980) both parameters had a significant effect (1st step: light intensity, $F_{1,7} = 8.44$; 2nd step: vertical extinction coefficient, $F_{2,6} = 11.68$). On 2. 11. 1981 there was a close relationship between Secchi disk transparency and light intensity ($F_{1,8} = 20.59$); no dependance on the vertical extinction coefficient could be detected.

Summarizing, surface light intensity changes, as well as fluctuations in vertical extinction coefficient, could influence Secchi disk transparency. It is recommended to carry out measurements between 11 a.m. and 2 p.m.

5 Light intensity at Secchi disk depth

The following equation is today generally used to calculate the vertical extinction of light in water:

$$I_z = I_0 \cdot e^{-k \cdot z}, \qquad (1)$$

where I_z = light intensity at depth z, I_0= subsurface light intensity (light intensity measured just below water surface), k = vertical extinction coefficient. Equation 1 can also be written:

$$z = -\ln(I_z/I_0) \cdot k^{-1}. \qquad (2)$$

Based on a general formula of R. A. Vollenweider (1960) representing the relationship of the vertical extinction coefficient of green light and the Secchi disk depth, R. Gächter (1971) determined the constants and obtained the following equation: $k_{GL} = 1.14/S^{0.83}$. k_{GL} = extinction coefficient of green light; S = Secchi depth. By using this equation, continuously decreasing (I_z/I_0)-ratios can be calculated with increasing depth (e. g. 2 metres: 0.28; 12 metres: 0.18).

Normally the vertical extinction coefficient of photosynthetically active radiation k_{PAR} is used in place of k_{GL} and a constant ratio (I_z/I_0) is assumed. In such a case the Secchi disk depth is inversely proportional to the vertical extinction coefficient (M. W. Lorenzen 1980); but the magnitude of the ratio differs considerably from author to author: S. Yoshimura (1938), 0.05; J. E. Tyler (1968), 0.10; A. M. Beeton (1957), 0.15; M. W. Lorenzen (1980), 0.20. I therefore decided to look at the intensity of light at the Secchi disk depth as a percentage of the subsurface light intensity. The results presented in Fig. 3 show

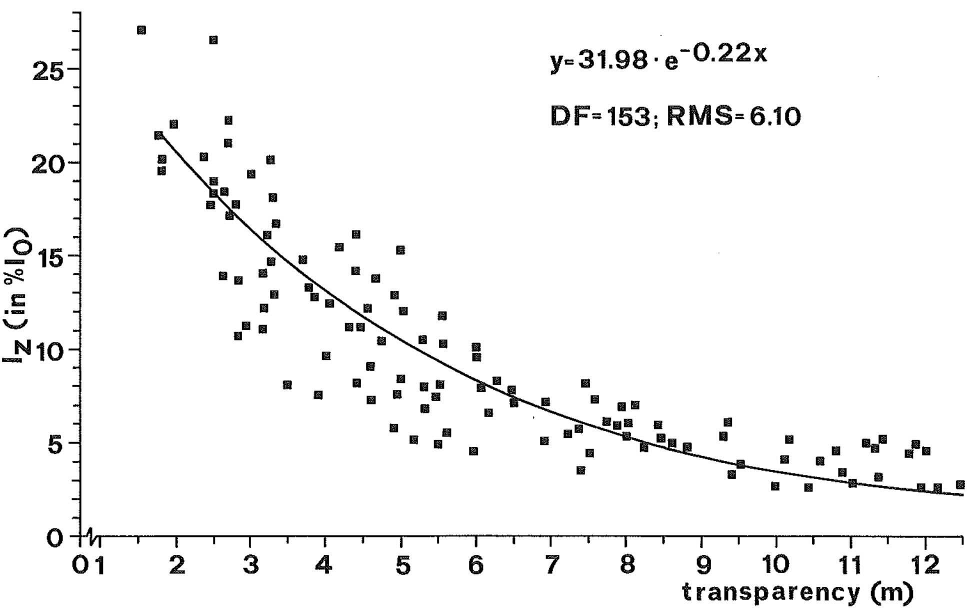


Fig. 3. Relationship between transparency and light intensity at Secchi disk depth (I_Z) in percent of subsurface light intensity (I_0) in the period 1979–1981.

Bild 3. Beziehung zwischen Durchsichtigkeit und Lichtintensität in der Secchi-Tiefe (I_Z) in Prozent der unmittelbar unter der Oberfläche gemessenen Lichtintensität (I_0) in der Periode 1979–1981.

clearly that the ratio (I_z/I_0) can not be constant. It varies from 0.22 at a Secchi depth of 2 metres to about 0.03 at 12 metres. The exponential decrease found resulted from a concentration decrease of suspended particles, causing less intense occultation and light scattering. It might also be influenced by the curtailment of the spectrum.

The phenomenon of occultation was described first by F. A. Forel (1901) and recently by W. T. Edmondson (1980) using a simple and instructive example. Occultation refers to the disappearance of the Secchi disk because of the screening effect of suspended particles (milk glass effect). A. Szczepanski (1958) demonstrated that within the depth of 0.5 to 10 metres the Secchi disk always disappears at a constant total amount of suspended particles above the Secchi disk ($\int_0^{zs} T(z)dz$ = constant, zs = Secchi depth, in metres; T(z) = suspended particles at depth z, in mg dry weight per litre). For the data from 1980 and 1981 a graphical evaluation of the relationship between transparency and the total dry weight of suspended particles above the Secchi disk confirmed the findings of A. Szczepanski: in a depth range of 1.5 to 16.7 metres the disk disappeared at a mean total dry weight of 104 mg (s = 20; n = 35). It can therefore be said that up to about 17 metres, occultation is the main cause of the disappearance of the Secchi disk.

A theoretical Secchi disk depth exists however where the concentration of suspended particles is very small (below 104 mg dry weight). In that case effects other than occultation are dominant as discussed in section 6.

6 Relationship between Secchi disk depth and vertical extinction coefficient (k_{PAR})

According to R. O. Megard et al. (1980) the vertical extinction coefficient (k_{PAR}) depends linearly upon concentrations (c) of chlorophyll *a*:

$$k_{PAR} = k_w + k_c \cdot c. \tag{3}$$

k_w= attenuation of light by water and substances other than algae; k_c = attenuation per unit concentration of chlorophyll *a* in water. Equation 3 is valid if k_w and k_c are constant. However this can not always be expected. In the case of high input of suspended particulate matter and intense biological decalcification, short-period changes in k_w occur; in addition, aggregates of algae give rise to other k_c values than does a suspension of small algal colonies or single cells. Nevertheless according to our own observations (F. Schanz und E. A. Thomas 1980) and those of other authors (A. Pfenninger 1902; L. Minder 1943; E. A. Thomas 1971) constant k_w and k_c values can be expected in Lake Zurich most of the year. Obvious extreme values have been excluded from this analysis.

The relationship between transparency and k_{PAR} is presented in Fig. 4: this is a two-term exponential relationship, with a range of validity extending from 1.5 to 13 metres. It is to be expected that k_{PAR} would be a minimum at the theo-

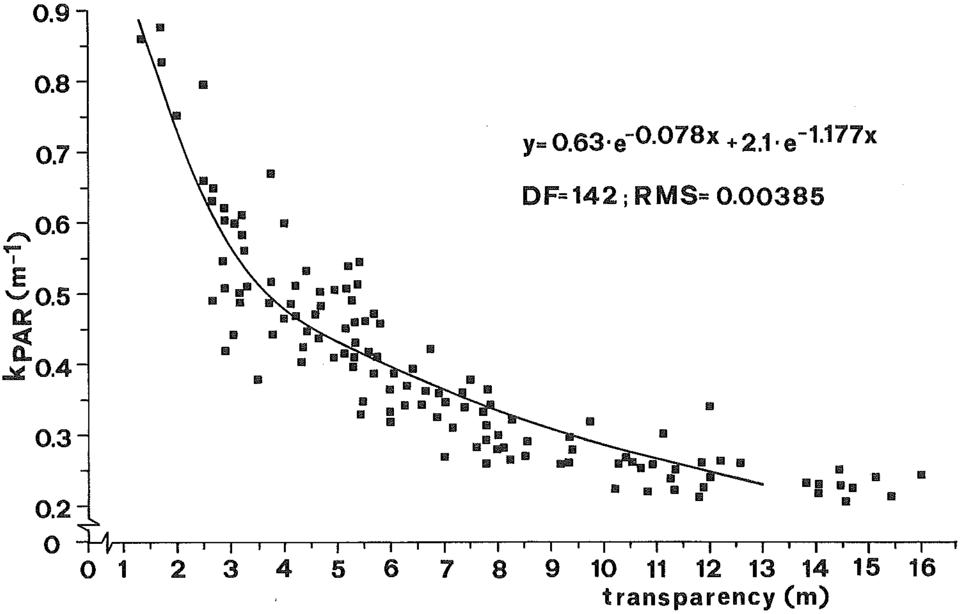


Bild 4. Beziehung zwischen Durchsichtigkeit und vertikalem Extinktionskoeffizienten (k_{PAR}) in der Periode 1979–1981.

Fig. 4. Relationship between transparency and vertical extinction coefficient (k_{PAR}) in the period 1979–1981.

retical maximum of Secchi disk depth in Lake Zurich. The Secchi depth maximum is determined by the attenuation of light by water in the complete absence of plankton (Equ. 3: $k_c = 0$) and by the ability of the human eye to perceive differences in brightness (F. Sauberer und F. Ruttner 1941).

An attempt was made to estimate the maximum Secchi disk depth by means of Fig. 5 which shows the relationship between transparency and mean chlorophyll concentration in the layer between the surface and the Secchi disk depth. It was assumed that chlorophyll containing species were dominant. Extrapolating the fitted curve, a Secchi disk depth of about 25 metres can be expected in the complete absence of chlorophyll *a*.

A second attempt was made by using the relative difference of brightness. For the human eye it has under experimental conditions a value of 0.0075 (E. G. Hutchinson 1957). By means of the equation published by F. Sauberer und F. Ruttner (1941), I found a relative difference of brightness of 0.022 at a Secchi depth of 16.7 m (assuming that the ratio of scattered light to direct incident radiation = 0.02, at 0.05 m depth; = 0.05, at Secchi depth). Extrapolating the available results from 10 to 16.7 m the theoretical value at 25 m is estimated to be about 0.01, which lies very close to the experimental value. The investigation shows indirectly that the calculated value of a maximum Secchi disk depth of 25 metres is realistic.

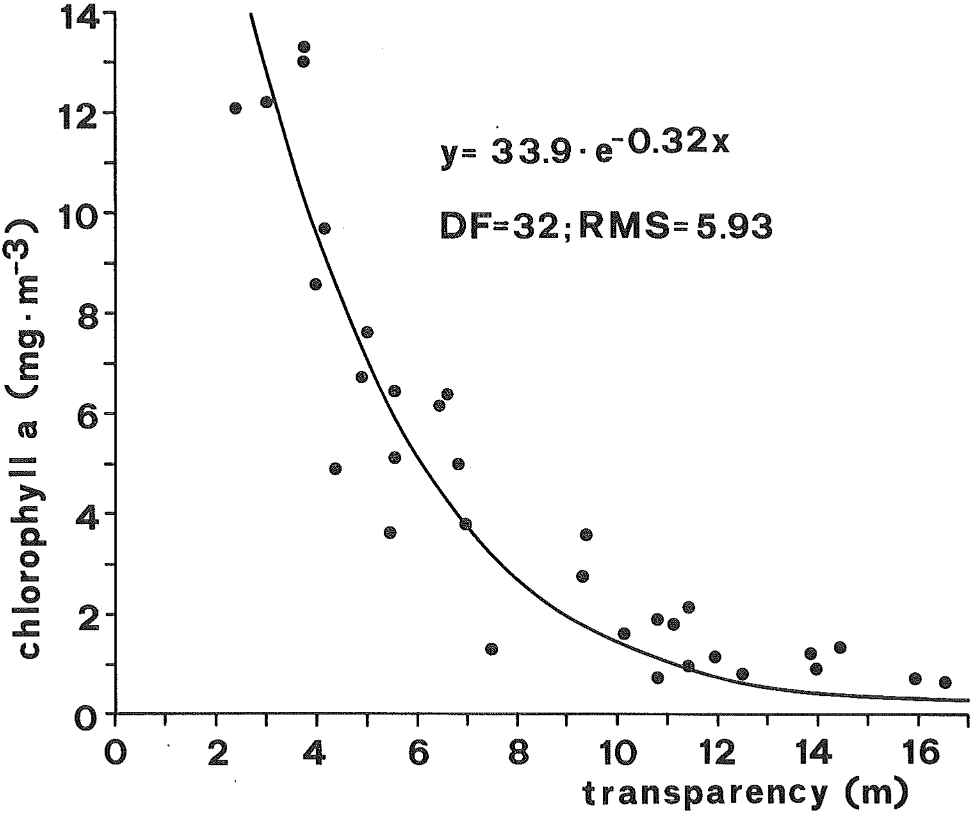


Fig. 5. Relationship between transparency and chlorophyll concentration (= mean from surface to Secchi depth) in the period 1980/81.

Bild 5. Beziehung zwischen Durchsichtigkeit und Chlorophyll-Konzentration (= Mittel von Oberfläche bis Secchi-Tiefe) in der Periode 1980/81.

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