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A MODEL FOR CALCULATION OF DIFFUSE LIGHT ATTENUATION (PAR) AND SECCHI DEPTH

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KEYWORDS: Secchi depth; diffuse attenuation; PAR; water quality; models.

ABSTRACT

To evaluate measures and to analyze the possibilities of achieving lake restoration goals a model was developed to calculate Secchi depth and diffuse attenuation for PAR (K_{par}). Inputs in the model are water the quality parameters chlorophyll-*a*, inorganic suspended matter, detritus and yellow substance. The model uses a spectral description of the radiative transfer of light. The coefficients relating the optical properties with the water quality parameters were found using an optimization procedure. The model was calibrated for four lakes in The Netherlands. Calculation of Secchi depth based on summer averaged input concentrations gave good results. Model results can be used to estimate the relative contribution of water quality parameters to the Secchi depth.

INTRODUCTION

The policy for water management in the Netherlands for the period 1990-1994 and management forecast for the turn of the century are described in the Third National Policy Document on Water Management (ANON., 1991). Water quality authorities can assign the functions drinking-water, bathing-water, water for cyprinids, water for salmonoids and shellfish water to the surface water. Apart from these functions, ecological objectives are indicated that aim at higher targets than the general environmental quality. Water quality standards are associated with each of these functions. There are two standards. The limit value applies to fresh water regardless of its function(s). This limit gives the maximum value for an environmental standard or environmental quality object. The target value refers to the situation that has to be achieved, the target situation. Target situations represent the scope to develop the water systems in relation to their use. But when water quality standards are not met measures have to be taken to improve the water quality, such as phosphate reduction or biomanipulation (GULATI *et al.*, 1990).

The goal in many lake restoration projects is lower algal biomass resulting in a higher Secchi depth, but increased Secchi depth is also a goal itself. Water transparency or clarity, measured using a Secchi disk, is important because it influences the public perception of water quality. It is therefore important to know the effect of decreasing concentrations of phytoplankton or suspended matter on Secchi depth, to estimate whether the lake restoration targets can be achieved.

The aim of this study was to estimate the relative contribution of components in surface water to the Secchi depth and the diffuse attenuation of light. These data can be useful when planning lake restoration measures. It can be used to analyze the influence of the different components on the light climate and to select the most dominant factor.

A model was developed to calculate Secchi depth and diffuse attenuation of Photosynthetic Active Radiation (PAR) also known as K_{par}. The model uses a spectral description of the radiative transfer of light. The inputs in this model are the water quality parameters chlorophyll-*a* as a measure for the algal biomass, tripton, detritus and yellow substance. Seston is defined as the total suspended matter including phytoplankton. Tripton is the non-algal particulate matter. Detritus is defined as tripton minus the inorganic fraction. Detritus can originate from phytoplankton but also from peat or macrophytes. With this model the effect of decreasing concentrations on Secchi depth and K_{par} can be estimated and evaluated against aims of lake restoration measures.

The model to calculate Secchi depth and K_{par} is given. Parameters used in the model were fitted using a global optimization procedure. This procedure was done for four lakes in The Netherlands. For these lakes the contribution of the relevant water quality parameters to the Secchi depth was calculated.

MATERIAL AND METHODS

Clarity is an important aspect of water quality, as it greatly influences the public's perception of water, and by that their willingness to use a particular water (EFFLER, 1988). In water management clarity is considered to be the visibility of submerged objects, which is measured with the Secchi disk. This technique has been standard limnologic routine for over a century. Its continued use must be attributed to the simplicity and robustness of the measurement (PREISENDORFER, 1986).

Secchi depth as a function of season provides a readily understood and useful record of phytoplankton growth and lake trophic status. The relation between chlorophyll, as a measure of the phytoplankton biomass, and Secchi depth has been subject of many studies (CARLSON, 1977; LORENZEN, 1980; MEGARD *et al.*, 1980; MEGARD and BERMAN, 1989). But the Secchi depth trophic state relation can be obscured by the presence of non-living particles, such as tripton. The factors determining the Secchi depth, K_{par} and light reflection are water, phytoplankton, tripton and dissolved organic matter (KISHINO *et al.*, 1984; PRIEUR and SATHYENDRANATH, 1981).

The inherent optical properties of surface water are the absorption coefficient a, the scattering coefficient b and the volume scattering function β (PREISENDORFER, 1961). The beam attenuation c is the sum of the absorption and scattering coefficients. These properties depend only on dissolved and suspended matter in the water and water itself and not on the geometry of the light field. The coefficients are defined for an infinitesimally thin layer of medium, illuminated at right angles by a narrow parallel beam of monochromatic light. The fraction of the incident flux that is absorbed, divided by the thickness of the layer, is the absorption coefficient. The fraction of the incident flux that is scattered, divided by the thickness of the layer, is the scattering coefficient. The angular distribution of the scattered light is specified by the volume scattering function. Secchi depth, K_{par} and reflectance while mainly dependent on the composition of the water body, also depend on the directional structure and spectral quality of the light field. They are apparent optical properties (PREISENDORFER, 1961).

Light is removed from the incoming light beams by absorption by coloured water components including phytoplankton and suspended or dissolved organic matter. The direction of the light can be changed by scattering of light by particles in the water. Scattering increases the pathlength travelled by light and therefore increases the chance of light to be absorbed. For the particles in water the scattering is mainly in the forward direction. A small fraction of light scatters backwards, causing the reflection of water. The directional structure of the light is described by an average cosine (μ), which can be compared with the hypothetical situation when there is only direct sunlight with sun angle (Θ) (μ= cos(Θ)) (KIRK, 1983).

Absorption, scattering, diffuse attenuation and reflection of light are wavelength dependent. However, Secchi depth and K_{par} are quantities that are determined by the complete visible spectrum, between 400 and 700 nm. In small wavelength intervals Lambert-Beer law may be applied to the diffuse attenuation coefficient (GORDON, 1989). However it may not be applied for broad wavelength bands such as PAR, where there is a significant wavelength dependency of absorption and scattering coefficients. Due to differential quenching of spectral bands with high attenuation coefficients K_{par} changes with depth (BOWLING and TYLER, 1986; JEWSON *et al.*, 1984).

To evaluate the effect of decreasing concentrations of water quality parameters on Secchi depth a link must be made between the inherent optical properties and water quality parameters. The spectral shape of absorption and scattering has been the subject in many studies (PRIEUR and SATHYENDRANATH, 1981; KISHINO *et al.*, 1984; DAVIES-COLLEY, 1984; DEKKER, 1993; KRIJGSMAN, 1994). The basis for the model calculations made in this study were literature spectra. When no spectra were available, some general assumptions were

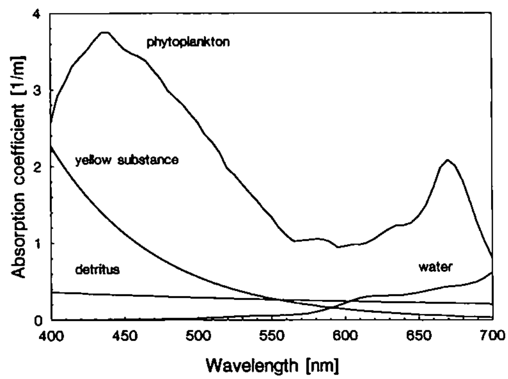

Fig. 1. Absorption spectrum of water and calculated absorption spectra of yellow substance, phytoplankton and detritus. The concentrations used to calculate these spectra are the summer average values of the Wolderwijd in 1989. Chlorophyll-*a* = 80 μg l^{-1}, tripton = 22 mg l^{-1}, detritus = 14 mg l^{-1} and $a_h(380)$ = 3 m^{-1}.

made about the spectral shape. The coefficients relating water quality parameters with absorption and scattering coefficients were estimated by optimization of the difference between calculated and measured Secchi depth and K_{par}.

The substances assumed to contribute to absorption and scattering were water (w), yellow substance (y), phytoplankton (ph) and tripton (t). Tripton contains inorganic suspended particles and detritus (d). The total absorption and scattering coefficients are the sum of the individual contributions (PRIEUR and SATHYENDRANATH, 1981; KISHINO *et al.*, 1984, DAVIES-COLLEY, 1984). Absorption takes place by water itself, dissolved yellow substances, phytoplankton, detritus and other coloured components, such as iron salts. All particles, phytoplankton and tripton (detritus and inorganic particles) scatter light (KISHINO *et al*, 1984). Each parameter will be discussed.

Water

Absorption and scattering coefficients of pure water were used (BUITEVELD *et al.*, 1994). The absorption of water is low compared with the absorption of yellow substance and phytoplankton in shallow, turbid eutrophic waters. Below 600 nm the absorption of yellow substance in most Dutch lakes is higher than the absorption of water (Fig. 1). The absorption of water increases strongly in the red and near infra-red part of the spectrum.

Yellow substance

Yellow substance (or aquatic humus or Gelbstoff) is a general name covering dissolved organic compounds of high molecular weight. Its definition consists in the method of isolation (primarily pore size of the filter paper) and measurement such as dissolved organic carbon concentrations, absortion and fluorescence, or any more elaborate set of properties. Yellow substance varies in concentration and in optical properties (ZEPP and SCHLOTZHAUER, 1981; BRICAUD *et al.*, 1981). The shape of the absorption spectrum of yellow substance can be described by the exponential function (1) (KALLE, 1966). The absorption decreases strongly with wavelength in a monotonous fashion.

$$a_y(\lambda) = a_y(380)\, e^{-k_y(\lambda-380)} \quad (1)$$

The exponential form (1) is usually applied in marine optics (PRIEUR and SATHYENDRANATH, 1981). The accuracy of this description was studied by BRICAUD *et al.* (1981) and ZEPP and SCHLOTZHAUER (1981). In this model $a_y(380)$ may be roughly equated with the concentration of yellow substance, while k_y describes the spectral shape. The measured value of k_y ranges from 0.01 to 0.02 nm^{-1} with an average value of 0.014 nm^{-1} (BRICAUD *et al.*, 1981). In Dutch inland waters the concentration of yellow substance $a_y(380)$ varies from about 1 to 63 m^{-1}, with a average value of k_y=0.016 nm^{-1} (KRIJGSMAN, 1994; DEKKER, 1993). The lakes that are considered here have average $a_y(380)$ values between 3 and 4 m^{-1}.

Phytoplankton

Phytoplankton both absorbs and scatters light. The form of the absorption and scattering coefficient and the values for the specific absorption coefficient $a_{chl}(\lambda)$ were taken from PRIEUR and SATHYENDRANATH (1981). Because the spectral forms of absorption and scattering are roughly complementary, and it is assumed that the beam attenuation c_{ph} is wavelength independent (SATHYENDRANATH and PLATT, 1988). This assumption was arbitrary because scattering depends on size distribution, refractive index and on the internal structure. The wavelength dependency of these particles ranges from λ^{-2} to λ^0 (VAN DE HULST, 1957; DUBELAAR, 1987). Improved modelling of the phytoplankton optical properties can be done when additional information on the size distribution and species of the phytoplankton is used (BRICAUD and MOREL, 1986). This information was however not available. An additional coefficient k_{ph} is introduced, which is used in the optimization. Higher values of k_{ph} will result in higher values for the specific K_{par} per mg chlorophyll-*a*. The form of the relevant coefficients is given below. For the meaning of symbols see Table 1.

$$C_{ph} = a_{ph}(550) + 0.12 chlorophyll^{0.63}\, k_{ph} \quad (2)$$

$$a_{ph}(\lambda) = (0.058 + 0.018 chlorophyll)\, a_{chl}(\lambda)\, k_{ph} \quad (3)$$

$$b_{ph}(\lambda) = c_{ph} - a_{ph}(\lambda) \quad (4)$$

Tripton

Tripton can be subdivided into an inorganic and a detritus fraction. However, there is at present no direct way to measure the detritus concentration. Here the detritus concentration was calculated based on measurements of seston dry weight, the inorganic fraction, chlorophyll-a and a conversion factor from chlorophyll-a to phytoplankton biomass, as given below. For the meaning of w_{chl} see Tabel 1.

$$detritus = seston - inorganic\ matter - w_{chl}\, chlorophyll \quad (5)$$

$$tripton = seston - w_{chl}\, chlorophyll \quad (6)$$

The conversion factor from chlorophyll-*a* to biomass is chosen to be 0.07 mg μg^{-1} (VAN DUIN, 1992). Some general assumptions were made to model the optical properties of tripton. The wavelength dependency of the beam attenuation was assumed to be inversely related to the wavelength. This is probably a reasonable choice for the particles present in water (VAN DE HULST, 1957). Further it is assumed that the inorganic part did not contribute to the absorption, where detritus absorbed light. Here the absorption of detritus was inversely related to the wavelength. Negative exponential curves were proposed to describe the shape (MASKE and HAARDT, 1987). For this study there was a lack of coefficients for the exponential model. Above 500 nm, the linear curve is a good approximation. Due to absorption by phytoplankton and yellow substance in the turbid eutrophic Dutch lakes there is very little light present below 500 nm. Increasing the total absorption by an exponential model for detritus absorption will therefore have little effect on Secchi depth and K_{par} calculations. The coefficients were calculated according to equations (7, 8 and 9). For meaning of symbols see Table 1.

$$c_t(\lambda) = k_1\, tripton^{k_2}\, \frac{400}{\lambda} \quad (7)$$

$$a_t(\lambda) = k_3\, detritus^{k_2}\, \frac{400}{\lambda} \quad (8)$$

$$b_t(\lambda) = c_t(\lambda) - a_d(\lambda) \quad (9)$$

Light model

A review of the physical basis of the Secchi depth and the sensitivity of the Secchi depth measurement as a function of environmental parameters was given by PREISENDORFER (1986). One of his conclusions was that the primary function of the Secchi depth measurement is to provide a simple visual index of the water clarity. DUNTLEY (1963), TYLER (1968) and PREISENDORFER (1986) showed that Secchi depth is inversely proportional to the sum of c en K_{par} according to equation (10). For meaning of the symbols see Table 1.

$$Z_{sd} = \frac{\Gamma}{c_{par} + K_{par}} \quad (10)$$

Γ has been shown to vary with difference in contrast between the white Secchi disk and the surface water (PREISENDORFER, 1986; DAVIES-COLLEY, 1988). This contrast difference depends on lighting conditions and the reflectance of the water, which is determined by the water constituents. Therefore, G is not a constant. DAVIES-COLLEY (1988) suggested the use of a black disk to surpass this problem. The values found for Γ ranged from 8.0 to 9.6 (KIRK, 1983; PREISENDORFER, 1986).

PREISENDORFER (1986) used beam attenuation and diffuse attenuation of photometric light. Here PAR is used, because of the availability of K_{par} measurements in addition to Secchi depth measurements. For PAR calculation the irradiance was converted to the amount of photons in the wavelength range 400 to 700 nm. There is a difference between the wavelength sensitivity of the eye and the sensitivity of a quantum sensor used for PAR measurement. But in the eutrophic waters that are considered here, maximum transmission of light occurs in the green part of the spectrum, due to the selective absorption in the blue and red parts of the spectrum. It is therefore believed that here PAR may be used.

E_{par} was calculated by dividing the spectrum into wavelength bands of 5 nm (KIRK, 1984). For each wavelength band $E_{par}(\lambda,z)$ was calculated from the incident $E_0(\lambda,0)$ using $K(\lambda)$. $E_{par}(\lambda,0)$ was derived from the irradiance, according to the radiation law of Planck with a temperature of 6000 K, and conversion to photons. Because we are in-

Table 1. List of symbols used.

Γ	: constant
λ	: wavelength, nm
m	: average cosine of incident light under water
$a(\lambda)$	: total absorption coefficient , m^{-1}
$a_{chl}(\lambda)$	: specific absorption coefficient chlorophyll-*a*, m^{-1} μg^{-1} l^{-1}
$a_{ph}(\lambda)$	: absorption coefficient phytoplankton, m^{-1}
$a_y(\lambda)$	: absorption coefficient of yellow substances
$a_y(380)$	: absorption yellow substance at 380 nm, m^{-1}
$b(\lambda)$	: total scattering coefficient, m^{-1}
$b_{ph}(\lambda)$	: scattering coefficient phytoplankton, m^{-1}
c	: speed of light , 3.10^8 m s^{-1}
$c(\lambda)$	: total beam attenuation coefficient, m^{-1}
chlorophyll	: chlorophyll-a concentration, mg l^{-1}
c_{par}	: beam attenuation of PAR, m^{-1}
c_{ph}	: beam attenuation phytoplankton, m^{-1}
detritus	: detritus concentration, mg l^{-1}
$E_0(\lambda)$	: Irradiance just below water surface, W m^{-2}
$E_{par}(z)$	: PAR at depth z, Ei m^{-2} s^{-1}
h	: Planck's constant, 6.6262 10^{-34} J s
$K(\lambda)$	: Diffuse attenuation coefficient, m^{-1}
K_{par}	: Diffuse attenuation of PAR, m^{-1}
k_{ph}	: parameter used for optimization related to phytoplankton
k_y	: constant, yellow substance, 0.016 nm^{-1}
k_1, k_2	: parameters used for optimization, tripton beam attenuation
k_3	: parameter used for optimization, absorption of detritus
f	: loss function
seston	: total suspended matter concentration, mg l^{-1}
tripton	: tripton concentration, mg l^{-1}
w_{chl}	: conversion factor from chlorophyll-*a* to biomass, 0.07 mg μg^{-1}
w_1, w_2	: weight factor for loss function
z	: depth, m
Z_{sd}	: Secchi depth
Subscripts	
c	: calculated
d	: detritus
m	: measured
ph	: phytoplankton
t	: tripton
y	: yellow substance

terested in diffuse attenuation the absolute value of the incident irradiance was considered of less importance.

For each wavelength band $K(\lambda)$ was computed from absorption and scattering coefficients (KIRK, 1984; 1991). $E_{par}(\lambda,z)$ was then integrated from 400 to 700 nm in order to obtain $E_{par}(z)$. K_{par} is calculated from E_{par} at two depths 0.1 m apart. Because K_{par} depends on the depth a choice has to be made for the calculation. Distinction was made between K_{par} for calculation of Secchi depth and K_{par} itself. For the calculation of the Secchi depth this depth was the 10% light level at 550 nm. When K_{par} is the aim, the calculation must resemble the way the measurement was done. K_{par} can be derived using a linear regression between $\ln(K_{par})$ and the depth. Measurements at greater depth then have a higher weight in the regression and K_{par} corresponds with K_{par} at greater depths. In the turbid Dutch inland waters this depth is between 1 and 2 m. K_{par} can be calculated from measurements of E_{par} at two depths, then these specific depths were used in the calculation. KIRK (1984) used and validated this formulation for the calculation of PAR. The different parameters were calculated as follows:

$$K(\lambda) = \frac{1}{\mu}\sqrt{a(\lambda)^2 + (0.425\mu - 0.19)\,a(\lambda)\,b(\lambda)} \qquad (11)$$

$$a(\lambda) = a_w(\lambda) + a_y(\lambda) + a_{ph}(\lambda) + a_d(\lambda) \qquad (12)$$

$$b(\lambda) = b_w(\lambda) + b_{ph}(\lambda) + b_t(\lambda) \qquad (13)$$

$$E_{par}(z) = \int_{400}^{700} E_0(\lambda)\, e^{-K(\lambda)z} \frac{\lambda\, 10^9}{c\, h\, 6.02\, 10^{23}}\, d\lambda \qquad (14)$$

$$K_{par} = \frac{1}{z_2 - z_1} \ln \frac{E_{par}(z_1)}{E_{par}(z_2)} \qquad (15)$$

The meaning of the symbols is listed in Table 1.

Secchi depth calculation also requires the beam attenuation. c_{par} was calculated in an analog way to K_{par}. First $c(\lambda)$ was calculated as the sum from $a(\lambda)$ and $b(\lambda)$ then $c(\lambda)$ was substituted in eq. (14) in the place of $K(\lambda)$. Next c_{par} was calculated from E_{par} at two depths. Where z_1 is the depth for the 10 % light level at 550 nm. The second depth was chosen near z_1 ($z_2 = z_1 + 0.1$).

RESULTS

In Fig. 1, the calculated absorption spectra of yellow substance, phytoplankton and detritus are shown corresponding to the summer average concentrations in Lake Wolderwijd in 1989 (Table 2). Detritus absorption is lower than phytoplankton absorption. Water absorption is higher than detritus or yellow substance absorption above about 600 nm. Below 500 nm absorption is particulary high due to phytoplankton and yellow substance.

Fig. 2 shows that the calculated diffuse attenuation $K(\lambda)$ is, in first approximation, determined by the absorption. Scattering increases the path-

Table 2. Some lake characteristics and summer mean values of the water quality parameters that influence the light climate, and the calculated Secchi depth using the model.

Lake	Year	Area	Chlorophyll	Inorganic matter	Detritus	Secchi depth	Calculated Secchi depth
		km^2	$\mu g\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	m	m
Wolderwijd	1989	18	80	8	15	0.31	0.37
Wolderwijd	1991	18	22	9	6	0.68	0.73
IJsselmeer	1992	1190	61	13	9	0.53	0.55
Markermeer	1992	680	23	37	8	0.34	0.32
Volkerakmeer	1992	46	11	3.4	1.8	1.73	1.58

Table 3. Coefficients in equations (1) - (10) found after minimizing the loss function.

	Wolderwijd	IJsselmeer	Markermeer	Volkerakmeer
Yellow substance				
k_y	0.016	0.016	0.016	0.016
Phytoplankton				
k_{ph}	3.25	2.38	2.47	1.62
w_{chl}	0.07	0.07	0.07	0.07
Tripton				
k_1	0.32	0.42	0.55	0.33
k_2	1.13	1.04	1.05	1.22
k_3	0.016	0.024	0.025	0.018
Secchi depth				
Γ	7.2	7.7	7.8	7.5

length of the light and therefore the chance of photons to be absorbed increases, causing higher $K(\lambda)$. Here K_{par} is 3.3 m^{-1}. This value is only 0.2 m^{-1} higher than the lowest values of $K(\lambda)$ around 600 nm. Scattering was about 3-5 times higher than $K(\lambda)$ and absorption.

While Secchi depth is determined by the sum of diffuse attenuation and beam attenuation, scattering will have more influence on the Secchi depth than it has on K_{par}. General relations between Secchi depth and K_{par} are therefore only possible when absorption and scattering correlate. This is true when only one component determines the optical properties. When more components are present scattering and absorption in general do not correlate, because the processes that influence phytoplankton growth and inorganic matter concentration (*e.g.* wind induced resuspension) differ.

Optimization

The coefficients $k_{1...3}$, k_{ph} and Γ were estimated, using a global optimization procedure (PINTÉR, 1990; VAN DER MOLEN and PINTÉR, 1993). Measurements of Secchi depth and K_{par} were used to minimize the following loss function (for meaning of symbols see Table 1).

$$f = w_1 (Z_{sd,m} - Z_{sd,c}) + w_2 (K_{par,m} - K_{par,c}) \tag{16}$$

The weight factors w_1 and w_2 were used to equalize the influence of both parameters on f. This was necessary because when Secchi depth is small K_{par} is large. During the optimization k_y and w_{chl} were kept constant. The coefficient k_2 was used to introduce a non-linear relation between scattering and tripton concentration. Both the linear option $k_2 = 1$ and the non-linear relation were tried. It appeared that the non-linear option gave better results. The final results of the optimization are given in Table 3.

The model was optimized for four lakes in the Netherlands. Some characteristics of the lakes including summer average values are given in Table 2. The data used for the optimization procedure was taken from other years than the data listed in Table 2. There is a good agreement between the calculated and measured Secchi depths.

Some differences were found in the coefficients. For the tripton beam attenuation, given by

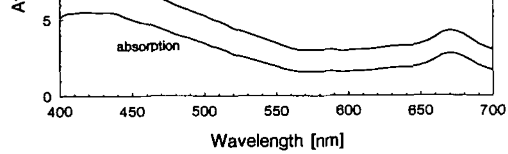

Fig. 2. Spectra of the calculated total absorption and scattering coefficients and the calculated spectrum of the diffuse attenuation coefficient $K(\lambda)$. The input used to calculate the spectra is the same as in Fig. 1. The calculated K_{par} is 3.3 m^{-1}. The calculated Secchi depth is 0.37 m.

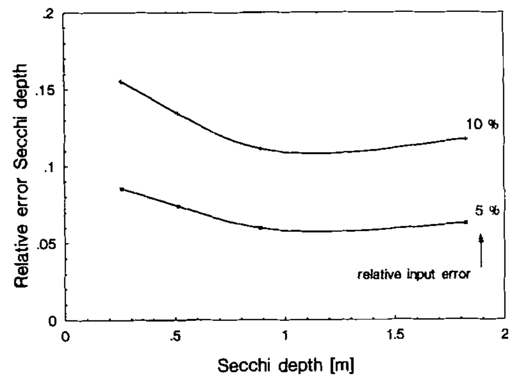

Fig. 3. Relative error in the calculated Secchi depth as a function of Secchi depth, based on relative errors in the input (chlorophyll, seston and inorganic matter) of 5 and 10%.

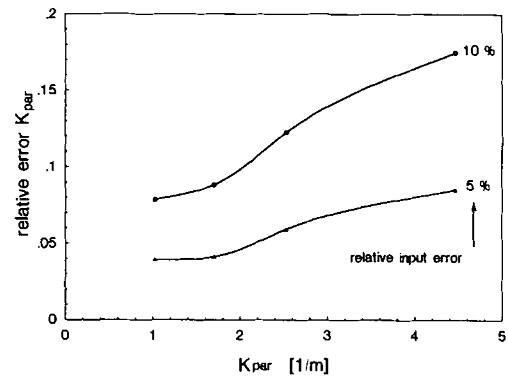

Fig. 4. Relative error in the calculated K_{par} as a function of K_{par}, based on relative errors in the input (chlorophyll, seston and inorganic matter) of 5 and 10%.

the coefficients k_1 and k_2, the two coefficients work in opposite directions, compensating for some of the difference. The Wolderwijd and IJsselmeer therefore have comparable beam attenuations, when tripton concentrations are the same. Also Volkerakmeer has a beam attenuation, comparable to those in the two lakes, when the tripton concentration is smaller than 5 mg l^{-1}. The Markermeer has a higher specific beam attenuation coefficient than the other lakes. This result can be attributed to much more fine silt in this lake (VAN DUIN, 1992). The coefficient k_3, describing the absorption of detritus, is highest in IJsselmeer and Markermeer. The coefficient k_{ph}, corresponding with phytoplankton specific attenuation, was high in the Wolderwijd and low in the Volkerakmeer. This result corresponded with the phytoplankton present in the lakes and values reported on the specific K_{par} per mg chlorophyll a (KIRK, 1983). Volkerakmeer was dominated by green algae whereas the Wolderwijd had an *Oscillatoria* dominance throughout the year. The values of Γ varied between 7.2 and 7.8, being lower than the range given by PREISENDORFER (1986).

Accuracy

The sensitivity of the model to uncertainties in the input was tested. The result gives an indication of the accuracy of the model. Relative deviation of ± 5 and ± 10% in the input concentrations of chlorophyll-*a*, seston and inorganic suspended matter were evaluated. Detritus had a higher relative deviation because it was calculated from the other parameters. The influence of yellow substance was evaluated separately.

A range of concentrations was selected to calculate Secchi depths up to 2.5 m and K_{par} up to 5 m^{-1} were calculated. Two additional data sets were made, namely one dataset plus the relative deviations and an other dataset minus the relative deviation. Using these three datasets Secchi depth and K_{par} were calculated. The error in the calculated Secchi depth and K_{par} is defined as the difference between the value calculated with the default dataset and the one calculated with the dataset plus or minus the relative deviation.

The calculated relative errors were plotted against the calculated Secchi depth using the default input (Fig. 3). The calculated relative error in the Secchi depth had a minimum around 1 m and was slightly higher than the relative error in the input. The error in the Secchi depth increased for lower values of Secchi depth. The results for the error in K_{par} were complementary with the results for Secchi depth calculation (Fig. 4). The relative error in K_{par} increased from about the same value as the relative input error at K_{par} = 1 m^{-1} up to twice the relative input error at K_{par} = 5 m^{-1}. These results indicate the level of accuracy to be expected when results are evaluated and calibrations are undertaken. When the model is used for estimation of Secchi depth or K_{par} after lake restoration measures it is advised to calculate a range of values based on known error margins in the input water quality parameters.

The influence of yellow substance on the calculated Secchi depth and K_{par} was evaluated by varying $a_y(380)$ from 0 to 16 m^{-1} while keeping the other concentrations constant using four dif-

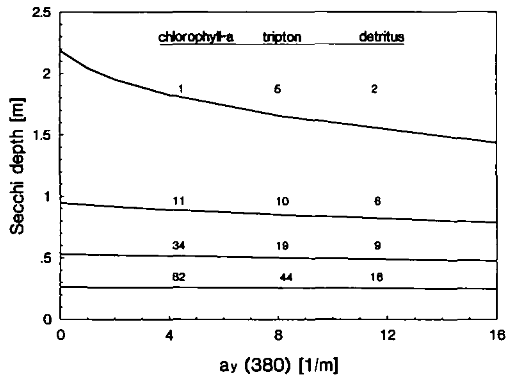

Fig. 5. Effect of increasing yellow substance concentration $a_h(380)$ on the Secchi depth. The concentrations used to calculate Secchi depth are shown in the figure.

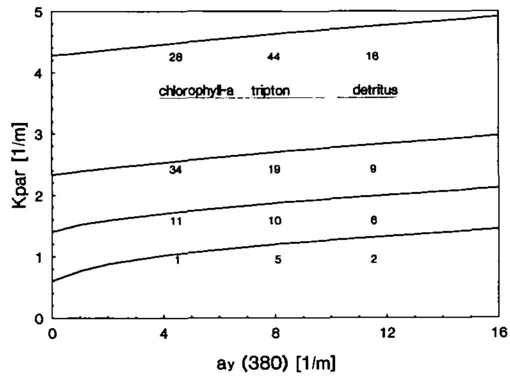

Fig. 6. Effect of increasing yellow substance concentration $a_h(380)$ on K_{par}. The concentrations used to calculate K_{par} are shown in the figure.

ferent input sets. Fig. 5 shows that for Secchi depths below 1 m the influence of yellow substance can be neglected. The influence of yellow substance becomes significant for Secchi depths above 1 m and increases in importance for clearer waters. K_{par} increased linearly with $a_y(380)$ almost independent of K_{par} (Fig. 6). In the area $a_y(380)$ <4 m^{-1} and K_{par} <2 m^{-1} deviation from linearity occurred. Then K_{par} increased stronger than in the linear area. In the linear region the increase in K_{par} with increasing $a_y(380)$ did not depend on the concentration of the other water quality parameters. In the case of the Secchi depth the other water quality parameters influenced the effect of $a_y(380)$ on the Secchi depth.

DISCUSSION

It was shown that Secchi depth and K_{par} can be calculated using a spectral light model. The inputs in this model are concentrations of yellow substance, chlorophyll-*a*, inorganic matter and detritus. Optimization of the coefficients in the model for different lakes was undertaken by a calibration procedure using field data. With this calibration procedure the relation between optical properties and the water quality parameters was determined. Because the prime object was to model Secchi depth and K_{par}, no validation of the calculated absorption and scattering spectra was done.

The accuracy of the model calculation depends on the accuracy of the input. The relative error in Secchi depth and K_{par} calculations ranged in the same way as the relative input error up to twice that error. The influence of varying concentrations of yellow substance on Secchi depth was small when Secchi depth was less than 1 m. This influence of yellow substance increased when Secchi depth increased. This influence is due to the approximately inverse relation between Secchi depth and concentrations. Change in one of the concentration will therefore have less effect on the Secchi depth when the Secchi depth is low.

K_{par} increased linearly with increasing $a_y(380)$, except for lower values of K_{par} and $a_y(380)$. Below $a_y(380)$ = 4 m^{-1} and K_{par} = 2 m^{-1} K_{par} increases more with increasing concentrations of yellow substance than in the linear region. This effect is caused by the broad wavelength band used for PAR. Within this broad spectral band the absorption and scattering are not constant. This variability causes the depth dependency of K_{par} but also non-linear effects in the relation between concentrations and K_{par} (BOWLING and TYLER, 1986; JEWSON *et al.*, 1984). Light is selectively removed from the spectrum at the wavelengths with higher absorption. With increasing depth the spectral width of the available light decreases. K_{par} is calculated with the available light. At greater depth wavelengths with higher absorption do not longer contribute in the K_{par} calculation. K_{par} increases with depth, because light is available at wavelengths with a lower absorption. In the case of yellow substance light is removed from the blue part of the spectrum. With increasing $a_y(380)$ the spectral width of the available light decreases, causing the non-linear effect.

The model can be used for the estimation of Secchi depth after lake restoration measures, and it

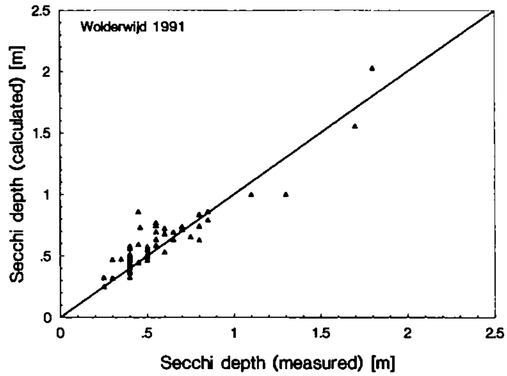

Fig. 7. Scatter plot of calculated Secchi depth against measured values for Wolderwijd in 1991.

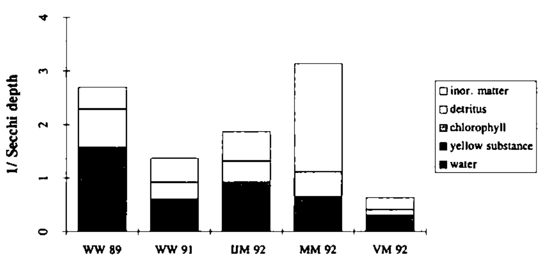

Fig. 8. Relative contribution of water, yellow substance, chlorophyll, inorganic matter and detritus to the inverse Secchi depth. The calculation is based on summer average values. The value of Secchi depth is given in Table 1. WW = Wolderwijd, IJM = IJsselmeer, MM = Markermeer and VM = Volkerakmeer.

can be used to estimate the relative contributions of the individual components to Secchi depth. This application is done for the inverse Secchi depth, because the concentrations are approximately linear with inverse Secchi depth.

In the first case the model results had to be extrapolated to situations that were to be expected after a lake restoration measure. Extrapolation to new situations assumes that the relations between concentrations and optical properties stay the same. The model calculations were carried out for the Wolderwijd. In this lake the fish stock was drastically reduced to improve the water quality and to increase the Secchi depth during the winter and spring of 1990-1991 (MEIJER *et al.*, 1992). The model was calibrated with Lake Wolderwijd measurements from 1978-1983. The measurements from 1992 were used to test the model. There is a good agreement between measured and calculated Secchi depth (Fig. 7). Especially the higher values were predicted well. Here the extrapolation was valid. The model was also applied to calculate Secchi depths based on summer averaged concentrations. Table 2 shows that this Secchi depth calculation also gives reasonable predictions.

In the second case the model was used to estimate the contribution of individual components to the reciprocal of the Secchi depth. A linear relation was derived between the reciprocal of the Secchi depth and concentrations of yellow substance, chlorophyll, inorganic matter and detritus. This linear relation between the inverse Secchi depth values and concentrations of water quality parameters will have a maximum Secchi depth, that can be predicted. This maximum Secchi depth value is called the background value and it is calculated when all the concentrations are zero. When field data were used this background value is too low. For Lake Wolderwijd the background Secchi depth was about 0.6 m. These results cannot be used for Secchi depth prediction of lake restoration measures. The problem of the low background Secchi depth value when using field data is probably caused by the limited range of Secchi depths available in the field data, the absence of higher values, and noise in and correlation between the measurements. Additionally the multiple linear regression between inverse Secchi depth and the water quality parameters gives a higher weight to lower Secchi depths.

In this study the calculated Secchi depth was used in the regression between the inverse Secchi depth and the relevant concentrations. The background Secchi depth increased to 5 m. The highest value calculated with the model itself was 160 m. This value agrees well with the maximum Secchi depths (150 -170 m) calculated by DIRKS (1990).

In Fig. 8 the contribution from water quality parameters, based on summer average values, to the inverse Secchi depth are given for the lakes listed in Table 2. These data can be useful when planning a lake restoration measure. It can be used to analyze the influence of the different components on the light climate and to select the most dominant factor. In these cases water and yellow substances have little influence on Secchi depth. However, for higher Secchi depth their relative influence will increase. In the Volkerakmeer the contribution of water to the inverse Secchi depth is smaller than in the other cases. This result is caused by the depth dependence of K_{par} (BOWLING and TYLER, 1986; JEWSON *et al.*, 1984). Due to higher water absorption above 600 nm K_{par} decreases with depth. Therefore, the influence of water absorption on the inverse Secchi depth depends on the value of Secchi depth itself.

It can be seen that a reduction of algal biomass to zero in the Markermeer will only result in a Secchi depth increase from 0.32 to 0.37 m. The dynamic character of the wind in combination with a long fetch (up to 30 km), limited depth (average 3.6 m) and silty sediments mean that resuspension of bottom material is the most important process in the Markermeer (VAN DUIN, 1992). In this case Secchi depth is dominated by resuspended inorganic matter.

When estimating the increase in Secchi depth due to a chlorophyll reduction it must be kept in mind that detritus will probably reduce. Realistic inputs in the model are an essential prerequisite for reliable answers. The spectral light model described can be used to evaluate lake restoration measures, to analyze the possibilities to achieve goals and targets. The model uses water quality parameters as input and gives information on Secchi depth and K_{par}. This is advantageous to the water manager, because it can be done without bothering about optical properties.

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