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REFLECTANCE MODELS FOR QUANTIFYING CHLOROPHYLL IN INLAND WATERS

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ABSTRACT

To develop the models for chlorophyll (CHL) estimation, the nature of a peak near 700 nm on the reflectance spectrum of water should be investigated. Simultaneous measurements of the reflectance spectra from 400 to 750 nm and relevant water quality constituent concentrations were carried out. A shift of the peak position and an increase of the peak magnitude, when chlorophyll concentration increased, were observed. The relationships of the magnitude and position of the peak to chlorophyll-a, were applied to several independent data sets. The parameters of the peak can be used as precise indicators of CHL content in inland waters.
Key words: radiance, algorithm.

INTRODUCTION

The red region of the reflectance spectrum is very important for the remote sensing of inland and coastal waters. This is due to several spectral features unique to CHL that appear in this region. A strong peak at about 685 nm in the upwelling radiance spectrum in natural waters was observed by Neville and Gower [1] There have been several attempts to explain this peak [1-5], but to date, it is not clear how its position and magnitude depend on CHL concentration.

The purpose of this paper is to present data on characteristic features of the reflectance spectrum between 680 and 720 nm and to contribute to the understanding of the nature of the peak. Having found the relationships between peak parameters and relevant constituent concentrations, they can be used to develop algorithms for the comprehensive remote sensing of water quality.

METHODS

Several thousand spectral irradiance measurements, along with simultaneous ground-data references, were taken in various water bodies [6,8]. In the study of the ecosystems, CHL ranged from 0.1 to 350 μg/l, the suspended matter ranged from 0.1 to 66 mg/l, and absorption coefficient of dissolved organic matter at the wavelength 380 nm varied from 0.1 to 12 m^{-1}.

A radiometer, recording from 400 to 750 nm, with a spectral resolution of about 1 nm and total field of view of 7^{o}, was used to measure the upwelling radiance and downwelling irradiance. Immediately after sampling, the fluorescence spectrum of each sample was measured using a Neva fluorimeter in the range of 640 to 750 nm with a spectral resolution of more than 0.7 nm.

The reflectance in the region of 450 to 750 nm was calculated for various concentrations of relevant constituents [2,7]. For the emission peak of chlorophyll at 680 nm a Gaussian distribution was assumed [2].

RESULTS AND DISCUSSION

The peak height was quantified by measuring the difference between reflectance at the wavelength where the maximum reflectance was observed, and the base line, interpolated from measurements at 670 and 730 nm [8]. Another way to quantify the peak height (R_{maxred}) was by normalizing it to the reflectance at 560 nm (R(560)). The ratio of R_{maxred}/R(560) versus the chlorophyll-a concentration for the first data set (the Don river 1983) was described by a function

$$Rmaxred/R(560) = 0.226\ Cchl^{0.362} \qquad (1)$$

with a coefficient of determination (r^2) of more than 0.93. Then the regression was applied to independent data sets (Table 1).

The increase in the peak height was accompanied by a shift in the position towards the longer wavelengths; meanwhile, the peak of the CHL fluorescence had a permanent position at 680 nm for all the samples measured. The peak position for CHL near 3 ug/l was observed at 685; it shifted to a longer wavelength reaching 715 nm for CHL at more than 100 ug/l. For the first data set the relationship peak position versus C_{chl} was obtained in the form:

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Table 1. Comparison of estimated (C_{est}), using equation (1), and measured (C_{meas}) chlorophyll-a concentration. a and b are parameters of the equation $C_{est}=a+b*C_{meas}$. Std Err is a standard error of chlorophyll estimation in μg/l. r is correlation coefficient.

Water body	a	b	r^2	Std Err
Northern Donec 1983	2.06	0.768	0.88	1.51
Don river 1984	0.33	0.912	0.95	1.61
Northern Donec 1984	1.73	0.855	0.91	1.85
Lake Balaton 1985	2.15	0.754	0.87	2.40
Lake Balaton 1986	0.85	0.903	0.83	2.70

$$\text{Peak position} = 682.14+0.322*C_{chl}, \text{ nm} \quad (2)$$

with r^2 = 0.95 and estimation error of the peak position less than 0.93 nm. Then Eq. 2 was applied to several independent data sets. Calculated and retrieved (from derivative of reflectance spectra) values of the peak position were compared (Table 2). The parameter "a" remained almost constant for these water bodies.

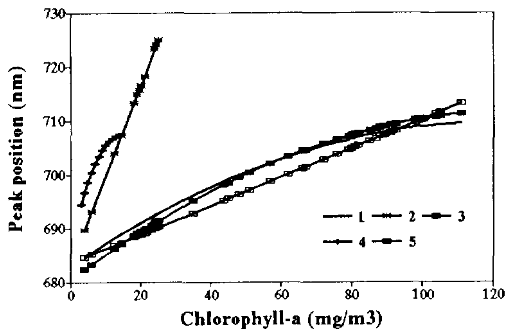

Figure 1. The peak position plotted versus CHL concentration. Comparison the results of calculations and measurements. Calculations: 1- Kishino et al. [9] for quantum fluorescence efficiency 2.5%; 2- Vasilkov and Kopelevich [4]; CHL fluorescence was not taken into consideration; 3- present work for quantum fluorescence efficiency 2.5%. Measurements: 4- Vos et al. [5]; 5- present work; the line presents eq. (2).

The measured values of the peak position were compared with various model calculations (Fig. 1 and Table 3). The calculation [9] (curve 1) is very close to our calculation and experimental results. By contrast, measurements [5] (curve 4) and the calculations [4] (curve 2) both show a sharp shift in the peak position when CHL concentration increases. The slopes of these relationships are three times steeper than the calculations [9] (curve 1), our calculations (curve 3) and measurements (curve 5).

A difference between the present results and those [5] may have many causes. In-situ phytoplankton fluorescence is influenced not only by the chlorophyll concentration, but also by the spectral distribution of the incident light, turbidity of water, phytoplankton species and phytoplankton state. A difference in these factors under artificial [5] and natural conditions can be very significant.

CONCLUSIONS

The following conclusions can be drawn for the conditions of this study :

1. The magnitude of the peak near 700 nm on the radiance spectrum correlates strongly with the chlorophyll concentration. The ratio $R_{maxred}/R(560)$

Table 2. Parameters of the relationships peak position = $a+b*C_{chl}$; b is standard deviation of b. a and Std Err of the peak position in nm.

Water bodies	a	b	b	r^2	Std Err
Northern Donec 1984	0.956	682.14	0.322	0.022	0.93
Don river 1984	0.785	683.73	0.257	0.032	1.68
Lake Balaton 1985	0.921	683.67	0.265	0.010	2.80
All water bodies together	0.933	683.42	0.268	0.007	2.41

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Table 3. Parameters of the relationship peak position = $a+b*C_{chl}+d*(C_{chl})^2$. a(380) is absorption coefficient of filtrate at 380 nm, C_{sm} is suspended matter concentration.

Authors	a	b	d	Notes
1. Kishino et al.,1986	683.0	0.44	-0.018	a(380)=0, C_{sm}=0
2. Vasilkov and Kopelevich, 1982	683.0	1.68	0	a(380)=1.0 m^{-1}
3. Present study calculation	680.4	0.49	-0.019	C_{sm}=5 mg/l, a(380)=3 m^{-1}
4. Vos et al., 1986	686.9	2.86	-0.084	C_{chl}=3-13.5 ug/l a(380)=5-12 m^{-1}
5. Present study measurements	683.5	0.27	0	a(380)=2-12 m^{-1} C_{sm}=4-66 mg/l

can predict CHL concentration for water bodies of different trophic states and allows the assessment of the CHL with an estimation error of less than 3 ug/l.

2. The position of the peak near 700 nm is very closely related to CHL concentration. For all the water bodies studied, a linear regression with r^2 more than 0.9 for this relationship and with an estimation error of less than 2.5 nm was obtained.

3. CHL fluorescence is the only cause of the peak for chlorophyll-a concentration up to 10 ug/l. For CHL reaching 15-20 ug/l, the parameters of the peak are caused by both CHL absorption and fluorescence. For CHL concentration above 30 ug/l, the absorption of CHL plays a dominant role in the formation of the peak.

4. The relationships of the magnitude and the peak position on the radiance spectrum to chlorophyll concentration can be used as precise indicators and predictors for the phytoplankton content in productive inland waters.

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