Journal of Plankton Research Vol.16 no.8 pp.993–1002, 1994

The use of high-spectral-resolution radiometer data for detection of low chlorophyll concentrations in Lake Kinneret

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Abstract. Chlorophyll distribution in Lake Kinneret was estimated in a period of low chlorophyll-*a* concentrations (3–7 mg m^{-3}) using remotely sensed data. The data set included high-spectral-resolution radiometric measurements in the range 400–750 nm, chlorophyll and suspended matter concentrations, Secchi disk transparency and vertical attenuation coefficients at 20 stations. The spectroradiometric data were used to create the algorithms suitable for quantitative determination of chlorophyll content. The present paper presents experimental field evidence showing that fluorescence can be successfully used for remote monitoring of chlorophyll-*a* content (with an estimation error <0.5 mg m^{-3}) in productive inland waters with a background of variable and relatively high suspended matter concentration.

Introduction

Lake Kinneret is the only large freshwater body in Israel. It supplies approximately one-third of the national water demand, and is important as a center for tourism and recreation, as well as commercial fishing. The lake undergoes considerable annual fluctuation in water levels, which may range from 209 to 213 m below mean sea level. This fluctuation in water level is currently a prime concern for water policy makers in Israel, as the long-term impact of these changes on water quality is largely unknown. A detailed monitoring program for the lake is the major tool for the acquisition of information needed for a rapid response to environmental questions. Algal abundance is a central parameter in this monitoring program, being determined both by microscopic count and measurement of chlorophyll (Chl) concentration (Berman *et al.*, 1992).

The distribution of phytoplankton in the lake is irregular, both spatially and temporally, causing severe sampling problems. An effective approach for monitoring the distribution of algae in Lake Kinneret could be remote sensing, which provides a synoptic view of the investigated area. Often, even a few images are useful as aids in the design or improvement of point sampling programs through the highlighting of the best sampling locations.

Until recently, Chl absorption in the blue region of the spectrum (e.g. Gordon and Morel, 1983) was the main parameter used in algorithms devised for the estimation of Chl by remote sensing. However, the blue/green ratio is sensitive to non-organic suspended particulate matter as well and, therefore, attempts to use these algorithms for the determination of Chl in productive waters have had only limited success. Although fluorescence line height has been used successfully for the remote detection of Chl (e.g. Neville and Gower, 1977;

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Gower, 1980; Doerffer, 1981; Fischer and Kronfeld, 1990), the best choice of a fluorescence algorithm is still problematic. Quantitative accuracy is limited by the varying fluorescent efficiency of different phytoplankton populations and by changes in water absorption that reduce the light available for inducing fluorescence. Although the number of potential variables modifying the specific fluorescence efficiency is high (Falkowski and Kiefer, 1985), experience gained from several observations indicates that for a limited period and area these variables change only within a limited range, thus allowing the successful application of the method to ocean and coastal waters (e.g. Gower, 1986; Fischer and Kronfeld, 1990). These algorithms can provide a reasonable degree of accuracy in prediction in defined conditions. For successful extrapolation to conditions other than those under which these algorithms were calibrated, adjustment of parameters is required to produce correct estimation of Chl.

Therefore, the reliability of remote measurements in productive waters, such as are found in Lake Kinneret, is still not guaranteed. In particular, a problem is posed during the summer–fall season by the combination of relatively low Chl content (3–10 mg m^{-3}) with a background of highly variable organic and non-organic suspended matter (Berman *et al.*, 1992).

The objective of our study was to create optical models of the lake, relating the reflectance obtained just above the water surface to the concentrations of Chl and other suspensoids in surface waters. This allowed the selection of spectral bands more sensitive to variation of Chl content, and the development of algorithms for precise Chl estimation. Several algorithms were used to assess Chl from radiometric measurements acquired on board ship, as a first step in using remote sensing technology to monitor phytoplankton distribution in Lake Kinneret.

Method

Twenty locations were sampled on 26 and 27 October 1992 (Table I). These were located in the northern part of the lake, where water depth ranged from 8 to 43 m. The sampling scheme was intended to cover as high a variation of Chl and non-pigmented suspended matter (SM) concentrations as possible, assuming that the Jordan river inflows provided the highest concentrations of the

Table I. Water quality parameters of Lake Kinneret at 20 stations on 26 and 27 October, 1992. Minimal, maximal and average values, and the standard deviation (STD) of parameters are shown

Parameter	Minimum	Maximum	Average	STD
Chlorophyll total, mg m^{-3}	3.1	7.3	4.74	1.13
Nanoplankton, mg m^{-3}	2.40	4.40	3.12	0.47
Seston dry weight, mg l^{-1}	1.80	4.83	2.93	0.80
Ash dry weight, mg l^{-1}	0.78	3.13	1.59	0.63
Attenuation coefficient, m^{-1}	0.16	0.82	0.49	0.17
Scattering coefficient, m^{-1}	0.94	4.42	2.41	0.88
Absorption coefficient, m^{-1}	0.08	0.44	0.27	0.09
Turbidity, NTU	1.20	4.20	2.11	0.70
Secchi disk depth, m	2.10	5.10	3.36	0.84

investigated parameters, while the lake center was expected to provide the lowest concentrations.

At each sampling station, the upwelling radiance, L_u, above the water surface and (indirectly) the downwelling radiance, L_d (with the aid of a standard reflectance white plate), were measured above the water surface with a portable LI-1800 spectrometer in the region 400–750 nm. The measurements were taken using a telescope with a field of view of 15°. Each observed radiance spectrum of water was divided by the appropriate downwelling radiance spectrum to give a reflectance as $R = L_u/L_d$. To minimize the contribution of specular reflected radiance during clear-sky conditions, the telescope was directed at the water surface at an angle of ~20° off the nadir in the opposite direction of the sun's azimuth, where the specular reflectance has its minimum. Vertical profiles of underwater irradiance were measured with a LI-185A radiometer; absorption and scattering coefficients of the water were calculated (Kirk, 1981a,b).

Water was taken with a 5 l Aberg-Rodhe sampler 0.0–0.5 m below the surface, and two 100 ml subsamples were immediately filtered (GF/F filters) and stored on ice in 5 ml 90% acetone. Upon return to the laboratory, 5 ml of 90% acetone were added to the filters, which were sonicated for 1 min and left in the dark at 4°C, overnight. Subsequently, the extract was cleared by centrifugation and measured fluorometrically (Holm-Hansen *et al.*, 1965).

Results and Discussion

Spectral features of reflectance

Although we tried to sample as wide a range of constituent concentrations as possible, the spatial distribution of these constituents was quite homogeneous. Chl ranged from 3.1 to 7.3 mg m^{-3} and SM ranged from 1.8 to 4.8 mg l^{-1}. The reflectance spectra were all similar in general outline (Figure 1). A sharp decrease around 440 nm corresponded to Chl absorption. A weak minimum at 520 nm, due to absorption of carotenoids, was also observed. The maximum, near 560–570 nm, was caused by minimum absorption by all phytoplankton pigments. Near 600 nm, the slope of spectral reflectance changed very sharply due to the spectral behavior of the absorption coefficient of pure water.

In the red region of the spectrum, a weak minimum between 620 and 630 nm was sometimes observed, which may correspond to phycocyanin absorption of picocyanobacteria (Malinsky-Rushansky and Berman, 1991). From 670 to 675 nm, the minimum of reflectance was recorded. The minimum was evident for Chl > 4 mg m^{-3} and hardly perceptible for Chl < 3.5 mg m^{-3}. A small fluorescence peak around 690 nm, which varied from 685 to 695 nm, was recorded in all spectra. This peak appeared at 685 nm at the station with maximum water transparency; in most spectra, the peak was close to 690 nm. The shape of this peak varied widely; the slope of the left side changed conspicuously from the spectrum to another. In several spectra, it declined sharply to 680 nm, and then a broad minimum between 670 and 680 nm was observed. In other spectra, a smooth slope connected the minimum at 670 nm and the peak at 685–695 nm. At wavelengths >690–695 nm, the reflectance

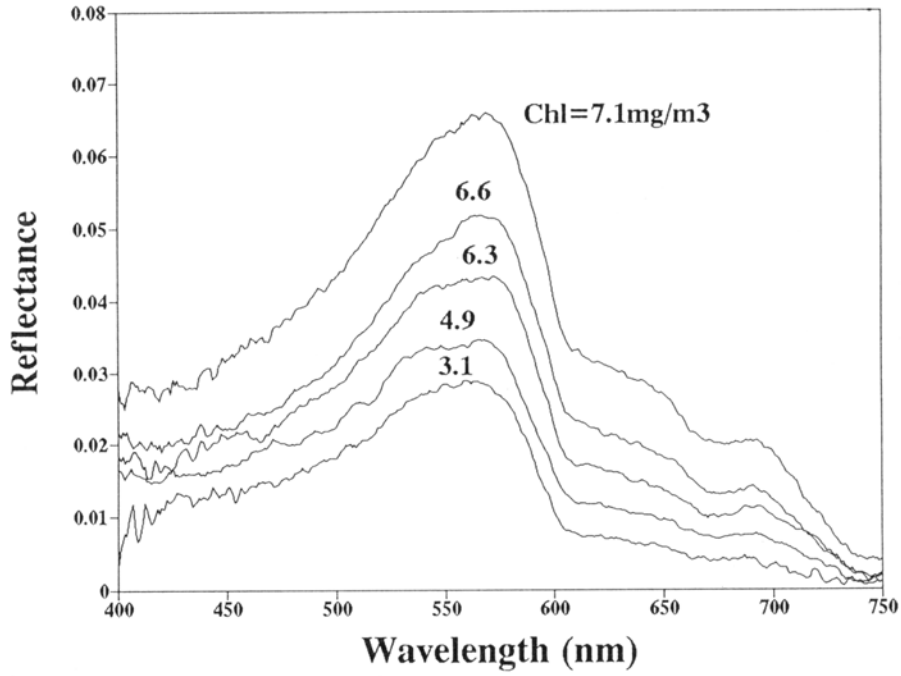

Fig. 1. Spectra of reflectance taken in Lake Kinneret on 26 and 27 October 1992. Chlorophyll-*a* concentrations are indicated.

decreased sharply. The spectra converged to a common reflectance value at 750 nm, a result suggesting that we could effectively block a high percentage of the surface-reflected light.

Lake Kinneret is a typical representative of Case II waters (Morel and Prieur, 1977), where Chl and SM concentrations are not closely correlated. In this experimental series, the square of the correlation coefficient between Chl and SM was <0.3. Therefore, it was not surprising that the correlation between the ratio $R(440)/R(550)$ [where $R(440)$ and $R(550)$ are the reflectances at wavelengths 440 and 550 nm] and Chl was $r^2 < 0.37$. A more precise Chl assessment ($r^2 > 0.57$ within an estimation error of Chl < 0.79 mg m^{-3} and significance level at $P < 0.05$) could be obtained using the reflectance ratio $R(520)/R(560)$ (Figure 2):

$$\text{Chl} = 19.35 - 17.42[R(520)/R(560)] \text{ mg m}^{-3} \quad (1)$$

Therefore, we concluded that the use of blue/green ratio algorithms (e.g. Gordon and Morel, 1983) is an inappropriate technique for Chl determination in Lake Kinneret.

Chlorophyll-a detection

The maximum of the observed reflectance at 685 nm at low Chl concentrations is

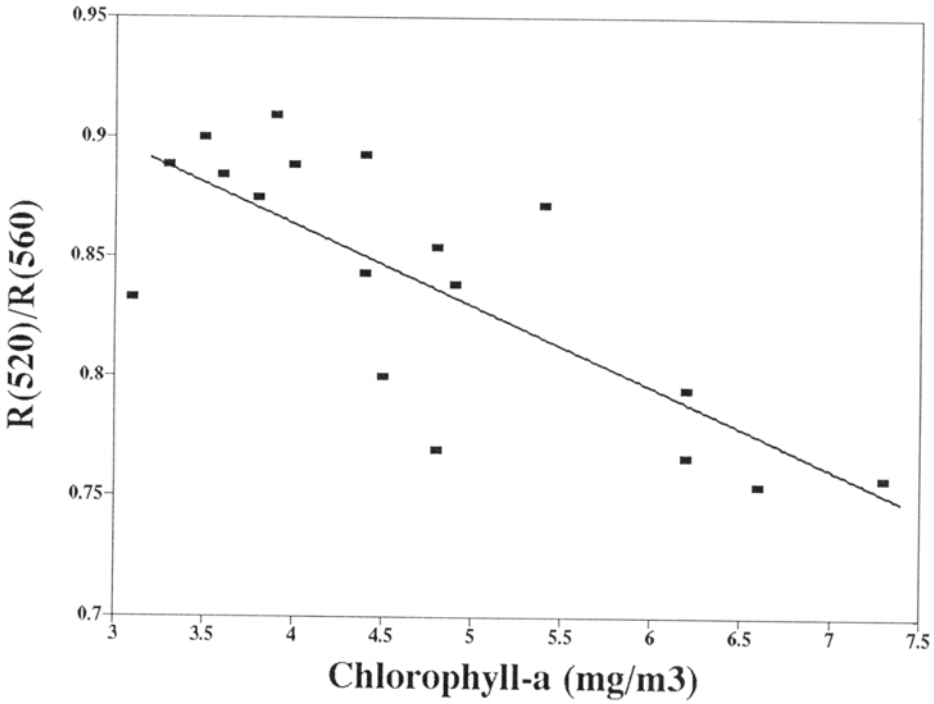

Fig. 2. Chlorophyll concentration plotted versus reflectance ratio $R(520)/R(560)$, measured by a LI-1800 spectrometer. The line represents equation (1).

caused by Chl-*a* fluorescence. This maximum was exploited to estimate Chl-*a* concentration in several ways. First, the fluorescence line height, *FLH*, at 685 nm above the linear base line which was drawn between 650 and 715 nm ($FLH_{650-715}$) was measured (Gower, 1980; Doerffer, 1981; Fischer and Kronfeld, 1990). The relationship:

$$\text{Chl} = 0.933 + 4.49 \times 10^3 FLH_{650-715} \text{ mg m}^{-3} \tag{2}$$

gave $r^2 = 0.64$, $n = 20$, $P < 0.01$ and allowed a Chl estimation with an error of <0.71 mg m^{-3} (Figure 3).

Two alternative algorithms were used to estimate the Chl concentration. A linear base line was fixed at 670 and 730 nm, and *FLH* at 690 nm was measured above the base line. A regression of the form:

$$\text{Chl} = 1.85 + 2.94 \times 10^3 FLH_{670-730} \text{ mg m}^{-3} \tag{3}$$

described the relationship with $r^2 > 0.73$, $P < 0.01$, and lowered the estimation error of Chl to 0.6 mg m^{-3} (Figure 4).

The accuracy of Chl estimation could be further improved by determining the sum of reflectance (*SUM*) above the base line in the region from 670 to 730 nm:

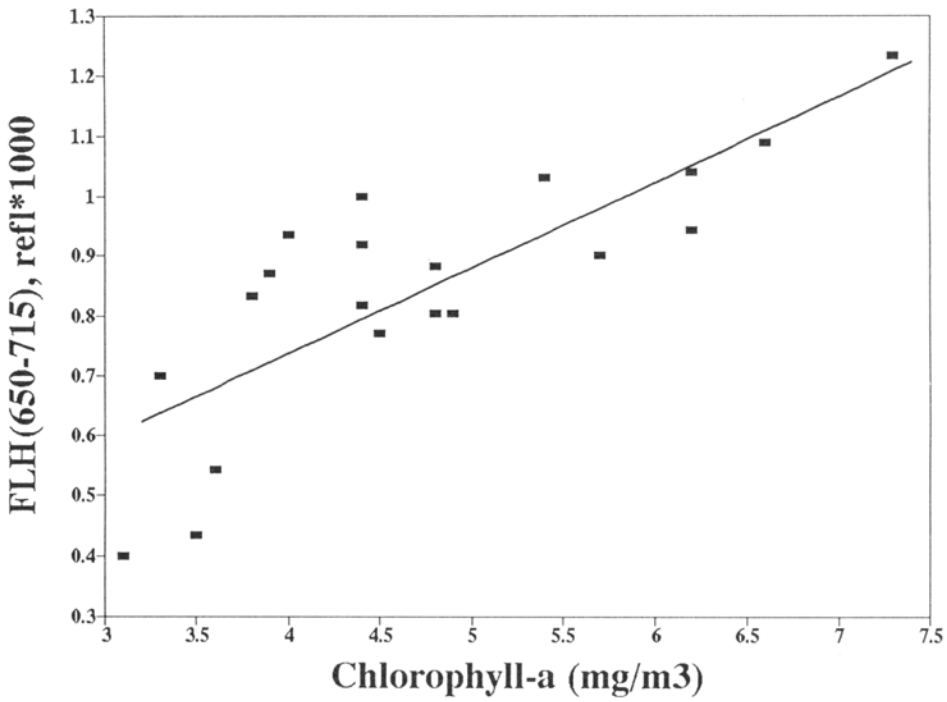

Fig. 3. Chlorophyll concentration plotted versus *FLH* at 685 nm, above the linear base line drawn between 650 and 715 nm. The line represents the equation $FLH_{650-715} \times 10^3 = 0.165 + 0.143 \times$ Chl.

$$\text{Chl} = 1.8 + 30 \times SUM \text{ mg m}^{-3} \tag{4}$$

This algorithm gave a Chl estimation error <0.48 mg m^{-3} and $r^2 > 0.84$, $P < 0.01$ (Figure 5).

To a certain degree, algorithms (3) and (4) avoided the problems of variation in peak position and shape. Both accounted not only for Chl fluorescence, but also for the Chl absorption at 670 nm, and enhanced the sensitivity of the measurements. Variability in the amount of SM caused changes in the slope of reflectance spectra from 600 to 750 nm. This tilted the base line for fluorescence, but did not prevent acceptably accurate determination of the line height and sum of reflectance above the base line.

Validation by an independent data set was required because of the semi-empirical nature of the models. This was done by applying equations (2), (3) and (4), derived from the October 1992 data, to calculate the Chl content by using reflectance measurements obtained in July 1993. The resulting predicted values were compared with the *in situ* measured Chl in July 1993. The closest correlations were obtained by using equations (3) and (4): r^2 values between predicted and measured values were 0.80 and 0.84, respectively, at $P < 0.01$ and $n = 25$. Estimation errors of Chl content ranging from 3 to 10 mg m^{-3} were <1.35 [using equation (3)] and 1.13 [using equation (4)].

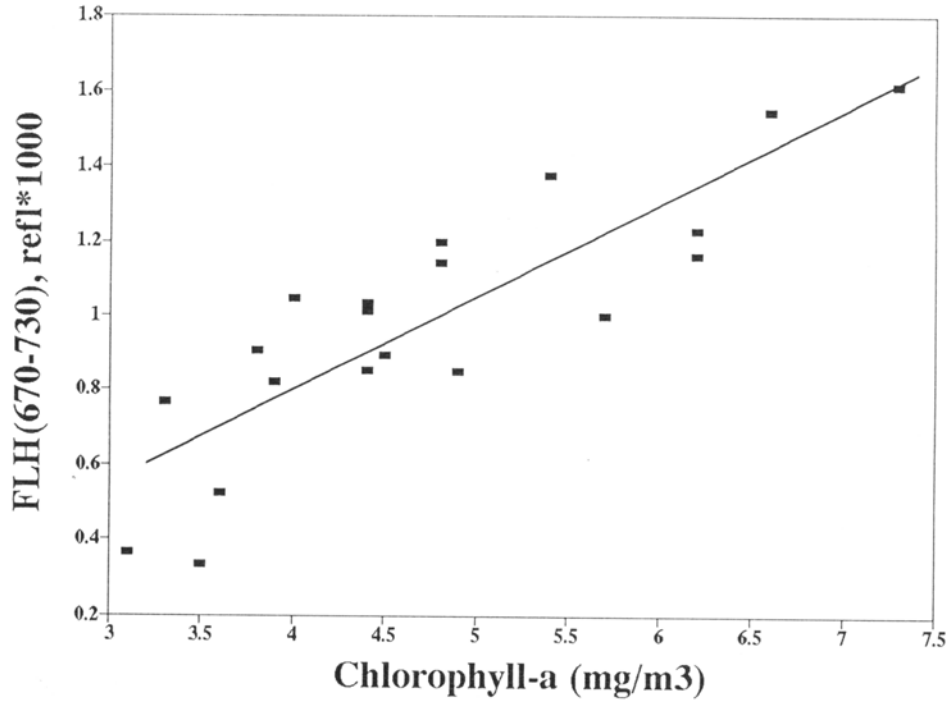

Fig. 4. Chlorophyll concentration plotted versus *FLH* at 690 nm, above the linear base line drawn between 670 and 730 nm. The line represents the equation $FLH_{670-730} \times 10^3 = -0.196 + 0.249 \times$ Chl.

In order to assess the efficiency of Chl fluorescence, radiances were calculated according to the optical properties of water, yellow substance, suspended matter and the absorption spectrum of phytoplankton (Prieur and Sathyendranath, 1981; Vasilkov and Gitelson, 1988; Fischer and Kronfeld, 1990). The fluorescence peak was centered around 685 nm, with a Gaussian distribution (Gordon, 1979). A good agreement was found between the measured and calculated radiance spectra, yielding a fluorescence efficiency of 0.25%.

Another estimation of fluorescence efficiency was carried out by comparing the slope of the relationship between the *FLH* above the base line from 650 to 715 nm and the measured Chl, obtained in our studies and the FLUREX experiment that took place in 1982 in the North Sea and Baltic Sea (Gower, 1986; Doerffer and Fischer, 1987). In that study, the slope of the relationship $FLH_{650-715}$ versus Chl was 0.20×10^{-3} reflectance increase mg^{-1} Chl m^{-3} for a fluorescence efficiency of 0.3% (Gower, 1986). In our measurements the relationship

$$FLH_{650-715} \times 10^3 = 0.165 + 0.143 \times \text{Chl reflectance mg}^{-1}\ \text{Chl m}^{-3} \quad (5)$$

had a slope of 0.143×10^{-3} reflectance mg^{-1} Chl m^{-3}, giving a fluorescence

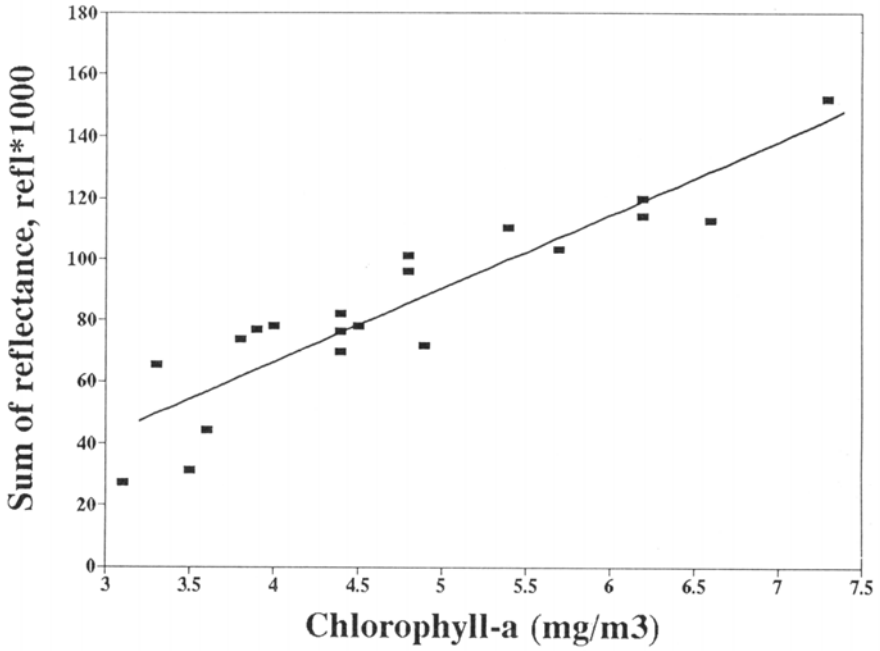

Fig. 5. Chlorophyll concentration plotted versus the sum of reflectance above the base line drawn between 670 and 730 nm. The line represents the best fit on a linear scale.

efficiency of 0.21%. This value is close to our assessment (0.25%) based on the optical properties of the water.

It is interesting to note that the slope of the relationship $FLH_{650-715}$ versus Chl obtained in our experiment is close to a minimal value (0.125×10^{-3}) derived from measurements in nine surveys carried out in coastal waters (Gower, 1986). Results from these experiments suggested a mean fluorescence output proportional to Chl-*a* equal to 0.24×10^{-3} of reflectance mg^{-1} Chl m^{-3}, with standard variation by a factor of ~1.8 on each side of this value. Our measurements in July 1993 gave a mean slope of the relationship $FLH_{650-715}$ versus Chl of ~0.15 $\times 10^{-3}$, close to results obtained in October 1992.

We also observed a higher amount of *FLH* above the base line through 650 and 715 nm when small phytoplankton cells were predominant (nanoplankton chlorophyll content >70% of total chlorophyll) than in samples having the same Chl concentrations, but containing <60% nanoplankton. This is probably due to the higher quantum yield of fluorescence for small particles (Alpine and Cloern, 1985). In addition, small particles scatter more light, such that a greater amount of energy leaves the water (Fischer and Kronfeld, 1990). This effect is strongly controlled by the real part of the complex refractive index, which should be smaller for larger particles (Vasilkov and Gitelson, 1988).

Our results are mainly relevant to inland and coastal waters, and the diverse and highly variable bio-optical properties that exist there.

Conclusions

The *FLH* at 690 nm above the base line through 670 and 730 nm or, alternatively, the sum of reflectance above the base line, were both shown to be directly proportional to Chl concentrations near surface lake water. An accuracy of estimation of ~0.5 mg m^{-3} was achieved. Even though the fluorescence intensity was low in comparison with the reflectance in the blue and green regions, we found it to be adequate for a quantitative measurement of chlorophyll concentration at least as low as 3 mg m^{-3} (the lowest value observed in these measurements) with high variation of suspended matter concentration. The highest chlorophyll levels in this study were 7.3 mg m^{-3}, but in more recent work we have found that these algorithms may be effectively applied within the range from 3 to ~26 mg m^{-3}. We have developed other algorithms for Chl concentration >10 mg m^{-3} which will be presented in a subsequent paper.

Our data provide new evidence that naturally induced fluorescence can be a very sensitive and powerful tool for the estimation of Chl content in near-surface waters of lakes, reservoirs, estuaries and coastal waters.

Further investigation is required in order to understand whether the parameters of the models are constant with time in the sampling area.

Acknowledgements

This work was supported by the Israel Water Commissioner's Office and by grant no. C-372/91 from the Israel Academy of Sciences and Humanities. It is a contribution of the J.Blaustein Institute for Desert Research of Ben-Gurion University of the Negev and Israel Oceanographic and Limnological Research Ltd.

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Received on June 2, 1993; accepted on March 19, 1994