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REFLECTANCE IN THE RED AND NEAR INFRA-RED RANGES OF THE SPECTRUM AS TOOL FOR REMOTE CHLOROPHYLL ESTIMATION IN INLAND WATERS - LAKE KINNERET CASE STUDY

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ABSTRACT

Signature analysis of reflectance spectra was used for the selection of the most suitable spectral bands for remote sensing of chlorophyll in inland waters. The parameters of the reflectance peak near 700 nm were employed for construction of algorithms for chlorophyll determination. The best model, validated by independent data sets, enabled estimation of chlorophyll concentration with an error < 0.6 mg/m^3 for period of low Chl concentration and < 6.5 mg/m^3 for period of the phytoplankton bloom. For the purpose of chlorophyll mapping in Lake Kinneret, the use of three relatively narrow spectral bands was sufficient. Radiometric data were also used to simulate radiances in the channels of TM Landsat and to find algorithm for chlorophyll assessment. The ratio (TM2-TM3)/TM1 was used to retrieve chlorophyll in the range 3-10 mg/m^3 with an error of < 1 mg.m^{-3}; the ratio TM4/TM3 was used to map chlorophyll in the range 10-200 mg/m^3 with 10 gradations.

INTRODUCTION

Water quality estimation by remotely sensed optical variables is based on wavelengths specific absorption and scattering of soluble and suspended matter in the aquatic medium. Of all the constituents chlorophyll (Chl) is the most important parameter for water quality characterization, being a probe of algal density. The estimation of Chl in marine oligotrophic waters has been successfully achieved by devising models which use the reflectance in the blue and green ranges of the visible light [1]. However in inland and productive coastal waters these models are hard to implement since several water constituents have noticeable impact on the light reflected by water in these spectral ranges, and they do not covary with Chl concentrations. In this paper novel models for Chl estimation based on the reflectance in the red and near infra-red ranges of the spectrum, developed for the subtropical Lake Kinneret, are presented.

METHODS

Two experiments were carried out in a period when the phytoplankton density was relatively low, however, the background concentration of non-organic suspended matter (SM) was high and variable. Two experiments were executed during *Peridinium* bloom, when Chl ranged from 3 to 187.5 mg/m^3. Therefore, the four experiments covered the typical situation of suspendoids concentrations in the lake.

At each sampling station, the upwelling radiance of the water, L$_w$, and the upwelling radiance of a standard reflectance BaSO$_4$ plate (L$_o$) were measured with a portable LICOR LI-1800 radiometer in the range from 400 to 850 nm. The measurements of upwelling radiance of the water have been done from the ship at the distance app. 2 m above the water surface using a telescope with a field of view of 15°. Each observed radiance spectrum of the water was divided by the appropriate spectrum of upwelling radiance of the reference plate to give a radiance reflectance as R=L$_w$/L$_o$.

For determination of vertical attenuation coefficient, downwelling irradiance in the range from 400 to 750 nm was measured using remote cosine receptor just above (E$_{dno}$) and under the water surface at the depth of 80 cm (E$_{dnz}$). Vertical attenuation coefficient was determined as K$_d$=Log(E$_{dno}$/E$_{dnz}$)/z. For determination of reflectance under the water, downwelling (E$_{dno}$) and upwelling (E$_{upo}$) irradiances were measured just under the water surface in the range 400 to 750 nm. Underwater reflectance was determined as R$_o$=E$_{upo}$/E$_{dno}$.

For each experiment TM Landsat images were acquired. The TM images had to undergo a geometrical and atmospheric corrections [2].

RESULTS AND DISCUSSION

The temporal and spatial variation found in Lake Kinneret was very high in all the variables we measured in our experiments (Table 1). In the winter-spring time the lake phytoplankton was dominated by

the large dinoflagellate *Peridinium gatunense,* which forms high crop stands. In the summer-fall period green algae, diatoms and small dinoflagellates were the most of the phytoplankton. This basic difference of phytoplankton composition was clearly displayed in the nature of the reflectance and diffuse attenuation spectra collected above and under the water surface by high spectral resolution radiometer.

Table 1: Timing, sampling intensity and water quality parameters of Lake Kinneret (Dry weight and turbidity data were kindly provided by A. Parparov)

	October 1992	March 1993	April 1993	July 1994
No. samples	20	40	37	39
Chlorophyll (mg/m^3)	3.1-7.3	5.1-185.0	2.4-187.5	5.3-26.0
Dry Weight (mg /l)	1.8-4.8	3.7-56.8	1.5-54.7	1.9-5.4
Secchi depth (m)	2.1-5.1	0.4-3.9	0.6-5.2	1.5-4.6
Turbidity (NTU)	1.2-4.2	2.4 -22.0	1.9-21.0	1.2-3.5

Vertical attenuation coefficient spectra

The spectra of vertical attenuation coefficient include several prominent features (Fig.1).
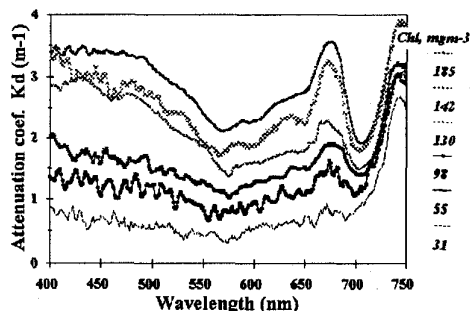

Fig. 1. Attenuation coefficient for downwelling irradiance. April 1994.

Decrease of attenuation coefficient was observed from 400 to 550 nm. For samples with higher Chl concentration (more than 50 mg/m^3), the reflectance increased reaching maximum at near 440 nm. The peak at 440 nm corresponded to the blue Chl-*a* absorption maximum. The attenuation coefficient decreased beyond 500 nm, with a shoulder at 480-500 nm. This absorption feature is due to carotenoids, which in the case of *Peridinium* are dominated by peridinin and diadinoxanthin [3]. The attenuation coefficient was lowest near 550 nm, where absorption of all photosynthetic pigments reached minimum. A maximum at 675 nm corresponded to the red Chl-*a* absorption peak. Near 700 nm, minimum of attenuation coefficient was recorded. The peak appeared at 700 nm for Chl < 15 mg/m^3 and reached 715 nm for Chl > 150 mg/m^3. Beyond 720 nm attenuation coefficient increased, achieving minimal values near 750 nm.

Reflectance spectra

The acquired reflectance spectra were all similar in general outline (Fig. 2a). 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 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. It corresponds to phycocyanin absorption of picocyanobacteria. From 670 to 675 nm, minimum of reflectance was recorded. The minimum was evident for Chl > 4 mg/m^3, and hardly distinguished for Chl < 3.5 mg/m^3. A small peak around 690 nm, which varied from 685 to 695 nm, was recorded in all spectra. This peak is a result of fluorescence emitted by phytoplankton [4]. Therefore, it is an important diagnostic feature of the reflectance spectrum, despite its modest size. At wavelengths beyond 690-695 nm the reflectance dropped sharply; the spectra converged to a common reflectance value at 750 nm.
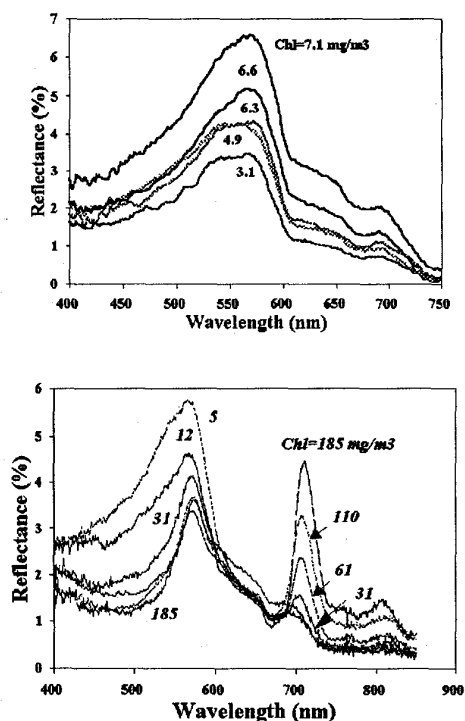
Fig. 2. Reflectance spectra obtained in October 1992 (a) and in March 1993 (b).

Representative reflectance spectra, acquired during *Peridinium* period are presented in Fig. 2b. For Chl concentrations higher than 20 mg.m^{-3} a minimum is seen in the blue range of the spectrum. The reflectance peaked between 550 and 580 nm. The peak width and its magnitude decreased with the increase of Chl concentration. In samples with the highest Chl concentration reflectance did not exceed 3% due to strong absorption by phytoplankton pigments. In the range from 590 to 650 nm the reflectance spectra of all the samples with Chl concentrations of more than 10 mg/m^3 displayed minimal variation.

A reflectance minimum was found at 670 nm. It was approximately 1% and was barely dependent on Chl concentration in a wide range from 10 to 187 mg/m^3. In samples with low Chl content, less than 5 mg/m^3, a wide shoulder was found at 683 nm, which corresponded to phytoplankton fluorescence. This peak was consistently found in Lake Kinneret during low Chl period (Fig. 2a). Red maximum

showed near 700 nm. The magnitude and position of this peak were strongly dependent on Chl content. The linear regression between the log(Chl) and the peak position could be summarized as follows (Fig. 3): Peak position = 677.1 + 15.5*log(Chl), $r^2 = 0.9$, with an estimation error of peak position of 2.76 nm.
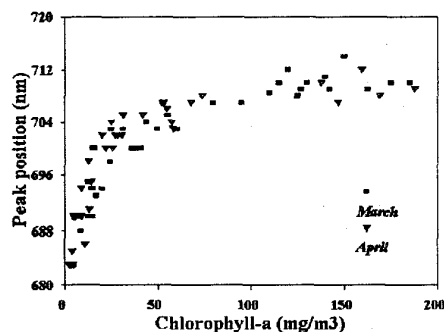

Fig. 3. Peak position versus chlorophyll concentration.

The blue absorption peak of chlorophyll-*a*, and carotenoids absorption are entirely masked by humus and tripton absorption (Fig. 1). The combined effects of dissolved organic matter, tripton and algae absorption at wavelengths shorter than 500 nm, and the increased scattering toward shorter wavelengths makes the attempt to separate the contribution of each constituents to the reflectance in this spectral region a difficult task.

For high Chl concentrations in the region above 500 nm, absorption slightly decreases, remaining, nevertheless, very high (Fig. 1). The reflectance in this region correspondingly remains low (Fig. 2b). The fact that absorption by peridinin, which *in vivo* peaks in the range from 490 to 510, is the governing factor of reflectance in the green region, is caused by the enormous concentrations of *Peridinium* during the bloom period.

It was discovered recently that the reflectance at 670 nm remains almost constant over a wide range of Chl-a concentrations [5-7]. When phytoplankton density increases, the reflectance near 670 nm should also increase, due to elevated scattering by phytoplankton cells. Concurrently, the increase in Chl-*a* absorption should lead to a decrease in reflectance. When Chl-*a* concentration is over 10 mg/m^3, the processes of absorption and scattering are almost in equilibrium. Phytoplankton density almost does not affect the reflectance at 670 nm and it primarily

depends upon non-pigmented organic and non-organic suspended matter concentrations.

For Chl concentrations of more than 20 mg/m^3, minimal attenuation was found at 700-720 nm (Fig. 1), conversely coinciding with maximum in reflectance (Fig. 2b). This maximum near 720 nm was observed recently in reflectance spectra in different types of water [5-8]. Decrease of Chl absorption and increase of pure water absorption results in minimum of combine absorption curve of algae and water [5, 9-10]. Increase of algal density leads to enhancement of scattering and, as a consequence, to increased reflectance.

For low Chl concentrations the region near 680 nm (natural fluorescence signal) is considered the most appropriate feature for gaining information on Chl concentration [11-12]. For Chl concentrations of more than 20-30 mg/m^3, scattering by phytoplankton cells is the dominant factor in the near infra-red region of the spectrum. It governs spectral behavior of both apparent optical properties: reflectance and vertical attenuation coefficient [5-7, 12].

Chlorophyll detection using high spectral resolution data

The index for Chl estimation should be invariant with respect to all water constituents, but Chl, and not be influenced by survey conditions. For these purposes wavelength where one dominant factor influences spectral feature variation (beside pure water) will be the most useful for determination of constituent concentration. Reflectance spectra acquired in the lake both for low and high Chl concentrations showed that the red reflectance maximum, near 700 nm, is the only feature expedient for our goal.

Our approach for Chl estimation was to use the reflectance height at the wavelength corresponding to peak maximum above the base line (RLH), spanned between 670 and 750 nm for low Chl period (RLH$_{670-750}$) and between 670 and 850 nm for high Chl period (RLH$_{670-850}$). We calculated the reflectance line height and to compare it to Chl concentration measured analytically.

For low Chl period (October 1992), the relationship was:
Chl = $1.84 + 29.4 *$RLH$_{670-750}$, $r^2 = 0.71$ with an estimation error < 0.6 mg/m^3

For high Chl period (March 1993) the relationship was:
Chl $= 1.77 + 40.77 *$RLH$_{670-850}$, $r^2 = 0.96$, with an error of less than 10.5 mg/m^3.

The validation of the model was made by using independent data sets obtained in April and July 1993,

yielded an estimation error < 1.35 mg/m^3 for low Chl period and < 6.18 mg/m^3 for *Peridinium* period..

Other possible approaches for Chl estimation is to use the sum of reflectance above the base line from 670 through 850 nm as a Chl indicator. The estimation errors of those algorithms were found of less than 0.48 mg/m^3 for low Chl period and less than 6 mg/m^3 for high Chl period [12].

Chlorophyll detection using Landsat Thematic Mapper data

In order to develop an algorithm for Chl estimation using TM data during low Chl period, the effect of SM on reflectance in the blue region of the spectrum had to be taken into consideration. For this correction, the reflectance in the red region of the spectrum was used. As back scattering due to non-organic SM increases, the reflectance increases across all the visible spectrum. In the red range the part of the reflectance due to Chl fluorescence was less than 5% of the total reflectance even for Chl = 7 mg/m^3 (the maximal concentration) and SM = 1.8 mg/l (the minimal concentration). The total reflectance in the region 620 to 690 nm depended almost solely on SM concentration. This conclusion was confirmed by the close relationship between Secchi disk depth and the sum of reflectance in the range from 620 to 690 nm [2]. Hence, band 3 of TM was used for subtraction from TM1 to correct for the additional radiance caused by scattering of non-organic suspended particles. The relationship between the ratio (TM1-TM3)/TM2 and Chl concentrations gave $r^2 = 0.71$ and allowed the estimation of Chl with an error < 0.68 mg/m^3. The prediction was examined using data extracted from TM image. Calculated from TM image Chl was compared to the Chl measured *in situ* and yielded an error < 0.85 mg/m^3. This allowed mapping of Chl ranging from 3 to 7 mg/m^3 with five gradations in concentration.

For *Peridinium* period the variation of simulated radiance in TM3 (600-690 nm) was minimal. Its maximal variation was found in TM4 (800-1100 nm). Those findings suggest that Chl assessment may be feasible using index constructed as a ratio TM4/TM3. This ratio will be maximally sensitive to Chl concentration and, to a certain degree, invariant with respect to survey condition. The comparison of the simulated radiances (TM4/TM3) with actually measured Chl concentration gave $r^2 > 0.92$.

The findings were examined using reflectances extracted from atmospherically corrected TM data. The correlation between TM-derived Chl and measured Chl

concentration, was $r^2 = 0.79$ with an error < 15.8 mg/m^3. This allowed mapping of Chl ranging from 5 to 185 mg/m^3 with 10 gradations.

CONCLUSIONS

The findings of this work support earlier results that the spectral range from green to near infrared is a suitable source for algorithm construction for Chl assessment in inland and productive coastal waters. We assume that for remote assessment of chlorophyll in inland productive waters, sensor for measurement of radiance with three spectral bands: 670 and 710 nm (with bandwidth 10 nm) and 850 nm (with bandwidth up to 40 nm) will be sufficient.

The stability of the proposed models depend on numerous factors. The main group concerns the inherent optical properties of algal cells, non-organic and detrital particles. Therefore, the parameters to be used in the models pertain to the nature of suspended and dissolved water constituents. Change in taxonomic composition of the phytoplankton, the intrinsic composition of the cells ("package effect"), the particle size distribution of non-living materials and the quantity of dissolved matter will affect the reflected signal.

In this study Chl concentration was estimated on the basis of a peak of reflectance near 700 nm that has different nature for low and high Chl concentrations. Fluorescence is the governing factor creating the peak in the red at low Chl concentrations, whereas at high Chl concentrations it is mainly caused by the interaction of Chl and water absorption. At this stage of our knowledge we could not distinguish between those two mechanisms when Chl concentrations are neither very low nor conspicuously high. For intermediate concentrations both processes effect the magnitude of this peak. Further investigation is required to understand the role of processes which govern the formation of the peak in the red range of the spectrum. Inherent optical properties of each optically active constituent and factors affecting quantum yield of natural fluorescence, as well, should be studied to create comprehensive algorithms for inland water quality monitoring.

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