Remote estimation of phytoplankton density in productive waters

A.A. Gitelson, Y.Z. Yacobi, J.F. Schalles, D.C. Rundquist, L. Han, R. Stark and D. Etzion

with 8 figures and 2 tables

Abstract: Most of the information pertaining to remote sensing of phytoplankton was developed for oligotrophic waters, where detritus and inorganic particles are scarce or their concentrations correlate with phytoplankton density. In our study we concentrated on inland and productive coastal waters, with the initial work done in Lake Kinneret, Israel. The primary objectives were: (1) to study the spectral features of reflectance of different water bodies during different seasons of the year, in order to find spectral features which are closely related to phytoplankton density; and, (2) to devise and validate algorithms for chlorophyll estimation using reflectance data as the measured variables. We found that the information gained from several spectral bands in the red and near-infra-red ranges of the spectrum was sufficient for the construction of algorithms for phytoplankton density estimation. These algorithms were validated in Lake Kinneret, as well as in other environments, with slight modification of the coefficients: the polluted water of Haifa Bay (Mediterranean Sea), fish ponds and wastewater reservoirs in Israel, and lakes with diverse trophic status in northwestern Iowa and eastern Nebraska (USA). Within the context of information essential for the estimation of chlorophyll concentration by remotely operated instruments, we discuss the requirements for satellite sensors to make them expedient tools for monitoring quality of productive aquatic ecosystems.

Introduction

The patchy nature of phytoplankton distribution is a challenge to any survey effort on larger water bodies. Therefore, remote sensing techniques, which offer a synoptic view of most or all

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the surface zones of water bodies in question, are a promising solution. The initial efforts to use remote sensing for phytoplankton monitoring were done in marine pelagic environments, where phytoplankton is often a dominant component of the suspended matter, and the total concentration of chlorophyll $a$ (Chl), a signature substance of phytoplankton, is mostly below 1 mg m$^{-3}$ (Morel & Prieur 1977, Gordon & Morel 1983, Kirk 1994, Bukata et al. 1995). Most inland waters are classified as Case II waters (Morel & Prieur 1977); in productive waters, the Chl concentration is often moderate to high and phytoplankton concentration is not tightly coupled to the density of total seston.

Chl concentrations in Lake Kinneret, Israel, range from less than 5 mg m$^{-3}$ to hundreds of mg m$^{-3}$ (Berman et al. 1992). The spatial distribution of Lake Kinneret phytoplankton is very heterogeneous, particularly when the dinoflagellate *Peridinium gatunense* in almost all years forms a dense bloom from February through May (Pollingher 1986, Berman et al. 1995). Funding considerations limit the sampling schedule to a few stations, and routinely to a single station, located above the deepest point of the lake. It is questionable whether this single station (or even a few stations) is truly representative for the overall condition. To overcome this problem, we initiated a program for remote sensing of chlorophyll in Lake Kinneret in October 1992. The primary aims were (1) to study the characteristics of the reflectance spectra during different seasons of the year, (2) to evaluate concepts developed for estimation of Chl concentration in inland waters (Gitelson 1986, 1993a, b, and (3) to devise algorithms for Chl estimation in Lake Kinneret from reflectance data. Following the establishment of algorithms for Chl detection in Lake Kinneret, an effort was undertaken to assess their validity in other productive and turbid water bodies in Israel and in the USA. In this paper, we present the summary of our work in those diverse water bodies, using remotely sensed data for the estimation of Chl concentrations.

**Materials and Methods**

Data were collected at several locations in Israel and in the north central United States. A list of water bodies examined is given in Table 1. Descriptions of optical properties of these water bodies have been published previously: Lake Kinneret (Gitelson et al. 1994 a, b) Yacobi et al. 1995), Haifa Bay (Gitelson et al. 1996), Carter Lake (Schalles et al. 1998), northwestern Iowa lakes (Jones & Bachman 1974), and wastewater treatment ponds (Oron & Gitelson 1996, Stark et al. 1996, Gitelson et al. 1997). In each experiment, upwelling radiance of

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>Chlorophyll $a$ (mg m$^{-3}$)</th>
<th>Dominant phytoplankton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Kinneret</td>
<td>winter-spring</td>
<td>2.4-330</td>
<td><em>Peridinium gatunense</em></td>
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<tr>
<td>Lake Kinneret</td>
<td>summer-fall</td>
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<td>Chlorophytes</td>
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<td>summer</td>
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<td>Diatoms</td>
</tr>
<tr>
<td>Carter Lake, USA</td>
<td>year round</td>
<td>20-280</td>
<td><em>Anabaena sp.</em></td>
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<tr>
<td>Fish ponds, northern Israel</td>
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<td><em>Microcystis aeruginosa</em></td>
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<tr>
<td>Wastewater ponds, Israel</td>
<td>spring-summer</td>
<td>69-2700</td>
<td>Chlorophytes</td>
</tr>
<tr>
<td>Haifa Bay, Israel</td>
<td>spring-summer</td>
<td>1-70</td>
<td>Dinoflagellates, diatoms</td>
</tr>
</tbody>
</table>
water ($L_w$) and of a reference plate ($L_{ref}$) were measured using high spectral resolution spectro-radiometers: LI-1800 (aquatic systems in Israel), Ocean Optics ST1000 (Carter Lake), and ASD (Iowa lakes). Reflectance spectra were then calculated as $R = L_w / L_{ref}$. Water samples were collected for analytical determination of Chl $a$ concentration in the laboratory. Detailed descriptions of the analytical methods and data processing used for treatment of the measured variables were presented in the above mentioned publications.

**Reflectance spectra**

Upwelling radiance of water contains information on the concentrations and composition of dissolved and suspended substances in the water, and is the "raw material" for remote estimation of concentrations of water constituents. Here we focused on spectral features of the upwelling radiance determined by chlorophyll $a$ absorbance and scattering by phytoplankton cells.

All water constituents have significant optical activity in the spectral range from 400 to 500 nm. This includes absorption by dissolved organic matter and scattering by particulate matter, which decrease toward longer wavelengths, and absorption by chlorophylls and carotenoids (e.g., KIRK 1994). Of special importance is a reflectance minimum near 440 nm (Figs. 1a and 2b), caused by Chl absorption; this feature is used in oligothrophic waters, in a reflectance (R) ratio at 440 nm and 550 nm ($R_{440}/R_{550}$), to estimate Chl concentration (GORDON & MOREL 1983). The minimum near 440 nm is often indistinct in reflectance spectra of productive waters, due to strong absorption by dissolved organic matter and scattering by particulate matter (Figs. 1b and 2a). In such waters, the reflectance near 440 nm becomes less sensitive to Chl concentration (GITELSON et al. 1994a, RUNDQUIST et al. 1994, SCHALLES et al. 1997). In the range near 490 nm another trough of reflectance is seen (Fig. 1a and 2b), caused by carotenoid absorption (GITELSON et al. 1995, YACOBI et al. 1995). In the case of Anabaena, the most abundant pigments of this group were zeaxanthin, myxoxanthophyll, echinenone and β-carotene (SCHALLES et al. 1998). In productive waters, as in Haifa Bay (Fig. 1a), Iowa lakes (Fig. 1b), Lakes Kinneret during the *Peridinium* period (Fig. 2a) and fish ponds (Fig. 2b), reflectance in the range 400 to 500 nm was low, with no pronounced spectral features within a broad range of total seston and phytoplankton densities. Thus, all optically active constituents (dissolved and suspended materials) contribute to reflectance in the range from 400 to 500 nm. A common characteristic of reflectance spectra in this range is low sensitivity of reflectance to phytoplankton density. Absorption by pigments is masked by absorption of dissolved organic matter and scattering by suspended matter.

In the range from 500 nm to near infra-red (NIR), the reflectance showed several distinct features: (a) a peak in the green range near 550-570 nm, (b) a trough near 625 nm, (c) a trough at 670-680 nm, and (d) a distinctive peak in the red-NIR boundary near 700 nm.

A prominent peak of reflectance in the green range represents the minimal absorption of all algal pigments. Scattering by non-organic suspended matter and phytoplankton cell walls are factors governing magnitude of reflectance in the green range (550 to 570 nm). Increase in concentration of particulate matter leads to increase in scattering and reflectance as well. Exceptions were Haifa Bay (Fig. 1a) and Lake Kinneret during the *Peridinium* bloom (Fig. 2a), where non-organic suspended matter load was very low (phytoplankton was responsible for more than 90 percent of dry weight), and phytoplankton was the only constituent that determined the optical properties of water. Increase in phytoplankton density led to an increase of
Fig. 1. Reflectance spectra of aquatic systems with low to moderate Chl concentrations. (a) Haifa Bay, June 1995. With increase in Chl concentration to 20 mg m$^{-3}$, the sensitivity of reflectance to Chl dropped significantly. In the range near 700 nm, reflectance was sensitive to Chl in a wide range of its variation. (b) Lakes in northwestern Iowa, USA, June 1996. Peak near 700 nm was found to be the only spectral feature sensitive to Chl concentration.

scattering by phytoplankton cells and pigment absorption. The latter was so strong that reflectance decreased and scattering by phytoplankton cell also increased. This decrease in reflectance appeared not only in the blue range but also in the green at a wavelength located far away from main absorption bands of chlorophylls and carotenoids. It was caused by strong absorption by carotenoids, mainly those within dinoflagellate cells, i.e., peridinin and diadinoxanthin.
Fig. 2. Reflectance spectra of aquatic systems with moderate to high Chl concentrations. (a) Lake Kinneret, February 1994. In the range 400 to 550 nm, absorption by pigments was so strong that it was hardly to distinguish between spectra with Chl ranging between 5 and 150 mg m$^{-3}$. Magnitude and position of the NIR peak depended strongly upon Chl concentration. (b) Fishponds in the Jordan Valley, Israel, February 1998. Blue green algae were dominant in the ponds; specific spectral feature of this algae can be seen as a gap near 626 nm.

The results from Haifa Bay (Fig. 1a) and in Carter Lake (SCHALLES et al. 1998) showed that the position of the reflectance peak was dependent on carotenoid concentration. With increase in carotenoid concentration, absorption increased and resulted in a decrease of reflectance and a shift of the peak position toward longer wavelength (from 550 to 570 nm Fig. 1a). In Lake Kinneret during the Peridinium bloom, absorption by carotenoids was so strong that the peak was found at 570 nm even for Chl concentrations as low as 5-15 mg m$^{-3}$ (Fig. 2a).
In waters dominated by blue-green algae a decline of reflectance in the range of 620-630 nm was noted (Figs. 2b, and 3) that was caused by the absorption of the cyanobacterial phycobilins (DEKKER 1993, GITELSON et al. 1995). The depth of this feature varied seasonally, in accordance with cyanobacterial abundance (Fig. 3, see also SCHALLES et al. 1998). Increase in phycocyanin concentration led to an increase in depth of the trough and, as a result, to shift of the green peak position toward shorter wavelengths of the (Fig. 3). Thus, in waters with blue-green algae the position green peak depends upon at least two factors: carotenoid and phycocyanin concentrations.

The trough near 670 nm is due to maximum absorbance by chlorophyll $a$ in the red range of the spectrum. For Chl concentrations of $> 20$ mg m$^{-3}$ the reflectance at 670 nm ($R_{670}$) is almost independent of Chl (Fig. 2a) and primarily depends on the concentration of non-organic suspended matter (GITELSON et al. 1993 a, b, DEKKER 1993, GITELSON et al. 1994b, YACOBI et al. 1995). At 670 nm, chlorophyll absorbance is offset by scattering of the cell walls and this wavelength is a point of minimum sensitivity of reflectance to algal density and Chl concentration.

In waters with low Chl concentrations, a peak of solar-induced Chl fluorescence was observed in reflectance spectra near 685 nm (Figs. 1a and b). With increase in Chl concentration, emitted fluorescence increased as well as the magnitude of the peak. The peak was used as an indicator of Chl concentration (e.g., NEVILLE & GOWER 1977, GOWER 1980, DOERFFER 1981, FISCHER & KRONFELD 1990, GKSS 1986).

With increase in Chl concentration above 15-20 mg m$^{-3}$ re-absorption of the fluorescence signal occurs and the magnitude of fluorescence peak decreases (KISHINO et al. 1986, GITELSON 1992, 1993); the nature of the peak is very different from that at low Chl concentrations (GITELSON et al. 1986, VOS et al. 1986, GITELSON 1992, 1993, GITELSON et al. 1993 a, b). This peak is an outcome of an interaction between the strong absorption by chlorophyll and water and the scattering by algal cells and other sestonic matter (GITELSON et al. 1986, VOS et al. 1986, GITELSON 1992, 1993).

The magnitude of the peak, as well as its position, depends strongly on Chl concentration (GITELSON 1992, 1993, GITELSON et al. 1994a, YACOBI et al. 1995, SCHALLES et al. 1998). The peak magnitude depends on scattering by all suspended matter and, thus, increases with increasing phytoplankton biomass. The magnitude of the peak correlated with Chl concentration via the link between Chl and algal biomass. As the algal biomass (or actually the active cell surface) increases, scattering and the reflectance increase. In this range of the spectrum, combined absorption by Chl and water is minimal; therefore, any scattering in addition to the basic scattering by non-organic suspended matter may be attributed to phytoplankton cell surface (GITELSON et al. 1994a, YACOBI et al. 1995).

Chl has low but significant absorption between 690 and 715 nm. With increasing Chl concentration, the pigment absorption offsets cell scattering at progressively higher wavelengths, and the position of the peak shifts toward longer wavelengths (Figs. 2 a, b, see also GITELSON et al. 1986, 1993 a, b, VOS et al. 1986, GITELSON 1992, RUNDQUIST et al. 1995, YACOBI et al. 1995, SCHALLES et al. 1998).

There were distinctive spectral features of reflectance (Fig. 2a) characteristic for the Peridinium bloom in Lake Kinneret. These reflectance spectral were conspicuously different from those observed in other seasons (reflectance spectra of Lake Kinneret in a non-Peridinium period resemble spectra obtained in Okoboji lakes, Fig. 1a, and in Haifa Bay, Fig. 1a, with Chl $< 10$ mg m$^{-3}$; see GITELSON et al. 1994b). Thus, even for single lake, different approaches have to be used for remote estimation of Chl concentrations at different seasons.
Algorithm construction and validation

Low Chl concentration. In productive, turbid waters with Chl concentrations below 20 mg m\(^{-3}\), the peak of Chl fluorescence near 685 nm was found to be the best spectral reflectance feature for estimating of Chl concentration. The height of the peak above a base line between 650 and 730 nm was used successfully for remote detection of Chl in Case II waters (e.g. NEVILLE & GOWER 1977, GOWER 1980, DOERFFER 1981, FISCHER & KRONFELD 1990, GKSS 1986). We slightly modified this algorithm by placing the base line between 670 and 730 nm which increased the sensitivity of Chl detection (GITELSON et al. 1994b).

The quantitative accuracy of the technique is limited by the variable fluorescence efficiency of different phytoplankton populations and by changes in water constituent absorption and scattering that reduces the light available for excitation of fluorescence. Although this technique was found to be useful for Chl detection, it is difficult to generalize and make comparisons based on previous studies, especially for inland waters with highly variable bio-optical properties. Nevertheless, the technique proved useful in Lake Kinneret during the non-Peridinium period when Chl concentrations were below 10 mg m\(^{-3}\) (GITELSON et al. 1994b) and in Iowa lakes (Fig. 7a). In Lake Kinneret, the estimation error of Chl, which ranged from 3.8 to 16, was less than 1 mg m\(^{-3}\); in Iowa lakes in the range of Chl concentration from 2 to 55 mg m\(^{-3}\); the estimation error was 7.8 mg m\(^{-3}\).

Moderate to high Chl concentration. The semi-analytical algorithms developed and tested in our work are all based on the use of reflectance in the red and NIR range of the spectrum, since other portions of the spectrum are irrelevant in productive, coastal and freshwater ecosystems (GITELSON et al. 1986, VOS et al. 1986, GITELSON 1992, MITTENZWAY & GITELSON 1988, MITTENZWAY et al. 1992, MILLIE et al. 1992, QUIBELL 1992, DEKKER 1993, GITELSON et al. 1993 a, b, 1994a, GOODIN et al. 1993, HAN et al. 1994, RUNDQUIST et al. 1995, 1996, YACOBI et al. 1995, SCHALLES et al. 1997, 1998). The basic concept of these algorithms is the inclusion of the spectral range which shows the maximum sensitivity to changes in Chl concentration and the range with the minimum sensitivity to variation of Chl concentration (GITELSON et al. 1986, 1993 a, b, 1994a, YACOBI et al. 1995). The latter accounts for non-pigmented suspended matter that causes variation in the reflectance. The magnitude and position of the reflectance peak near 700 nm were found to be the most sensitive variable for algorithms, and the reflectance at 670 nm was the least sensitive to changes in algal density, especially for Chl > 15-20 mg m\(^{-3}\).

A simple reflectance ratio \(R_{700}/R_{670}\) was first used as a predictor of Chl concentration (GITELSON et al. 1986, MITTENZWAY & GITELSON 1988, MITTENZWAY et al. 1992, GITELSON et al. 1993 a, b). The \(R_{700}/R_{670}\) ratio (Fig. 4a) was applied to our data obtained in highly diverse aquatic ecosystems dominated by different algal assemblages: Anabaena sp. (Fig. 5a), Microcystis aeruginosa (Fig. 5b), and Peridinium gatunense (Fig. 6). The relationship between the \(R_{700}/R_{670}\) ratio and Chl concentration was linear up to concentrations of approximately 180-200 mg m\(^{-3}\), but turned exponential at higher concentrations (Fig. 5b). To estimate the accuracy of Chl prediction in Lake Kinneret during the Peridinium bloom, the combined dataset (reflectance spectra and Chl concentrations) was separated into model-development and model-testing subsets. For the model-development subset, data collected in March 1993 were used (Fig. 6). Validation was done using data collected in April 1993. Predicted Chl concentrations were calculated using reflectance from the model-testing subset with regression coefficients for the model-development dataset equation (solid line in Fig. 6). The accuracy of Chl...
Fig. 3. Demonstration of accessory pigment effects on reflectance spectra. Two representative spectra from Carter Lake for June 4 and July 29, 1996. Chl concentrations were almost the same, but on July 29, phycocyanin (PC) concentration was much higher. As a result of higher PC concentration, the depth of a trough near 625 nm was at least twice more than that on June 4. The spectrum taken in July 29 shows a shifted position of the ”green” peak towards shorter wavelengths.

prediction was tested against Chl concentrations actually measured. Root-mean square deviation of predicted Chl values from measured values did not exceed 18 mg m$^{-3}$ (insert in Fig. 6).

Following the initial experiments in Lake Kinneret, several algorithms were developed for estimation of Chl concentration. These were based on the following variables: (a) the height of the peak near 700 nm above the baseline drawn from 670 to 750 nm (Fig. 4b); (b) the area delimited by the reflectance curve and the above-mentioned baseline (Fig. 4c); (c) the position of the peak in the NIR range. These algorithms were based on following concept. The trough at 670 nm is the wavelength of maximum absorbance by Chl in the red range of the spectrum. At this wavelength, Chl absorbance and scattering by algal cell walls are almost in equilibrium, and $R_{670}$ shows minimum sensitivity to Chl concentration. For a Chl $> 20$ mg m$^{-3}$, $R_{670}$ primarily depends on concentration of non-organic suspended matter (GITELSON et al. 1993a, 1994b, DEKKER 1993, YACOBI et al. 1995). Reflectance beyond 750 nm depends on both organic and non-organic suspended matter concentrations and is insensitive to algal pigments (HAN et al. 1994); the variability of $R_{750}$ is comparatively small because of strong water absorption in the NIR range. Thus, the slope of the baseline between 670 and 750 nm depends primarily on scattering by water constituents rather than phytoplankton. With changes in concentration of non-organic and non-pigmented organic suspended matter concentration, the slope of the baseline changes but this has minimal influence on the height and area of the 700 nm peak above the base line. Therefore, the height of the peak and the area above the baseline between 670 and 750 nm depends mainly on phytoplankton density and was used as a quantitative measure for this parameter.

The regression of reflectance height at 700 nm above the baseline from 670 to 750 nm (Fig. 4b), as well as area above this baseline (Fig. 4c), and the position of the NIR peak (GITELSON
Fig. 4. Algorithms for estimation of Chl concentration. (a) Ratio of the peak magnitude to reflectance at 670 nm; (b) Reflectance height above the base line between 670 and 750 nm; (c) Area above the base line between 670 and 750 nm.

1992, 1994), against Chl α concentrations yielded high correlation coefficients, always $r^2 > 0.90$ (GITELSON et al. 1994a, YACOBI et al. 1995). The developed algorithms were validated by
recurrent experiments in Lake Kinneret, as well as in other environments, including Iowa lakes dominated by diatoms (Fig. 7a) and Haifa Bay with dinoflagellates and diatoms (Fig. 7b), both with low to moderate Chl concentrations (Table 1). The algorithms were also used to estimate Chl concentrations in wastewater ponds, where chlorophytes dominated with extremely high (70-750 mg m\(^{-3}\)) Chl concentrations (Figs. 7c). In all aquatic systems studied, the algorithms proved on effective method of estimating Chl concentration.

Basically, in all instances the same algorithms may be applied. However the coefficients of the relationships between Chl concentration and remotely measured variables should be adjusted for each case separately (Table 2). The suitability of those algorithms for completely different water bodies studied, from mesotrophic Iowa lakes to hypereutrophic wastewater ponds, underlines the physical rationale behind the choice of the spectral reflectance features used. For all inland waters studied, excluding wastewater ponds, the coefficients b in the rela-
Fig. 6. Validation of the reflectance ratio algorithm, $R_{700}/R_{670}$, for estimation of Chl concentration in Lake Kinneret. Chl concentrations were predicted by ratio $R_{700}/R_{670}$ measured in April 1993. Relationship $R_{700}/R_{670}$ vs. Chl (solid line), obtained in March 1993, was used to calculate predicted Chl. Then, predicted Chl was compared with measured Chl concentrations (insert). Error of Chl prediction, determined as root-mean square deviation of predicted from measured Chl values, did not exceed 18 mg m$^{-3}$. The slope of the relationship $R_{700}/R_{670}$ vs. Chl changed in various experiments (see Figs 5 and 6). In the cases presented herein, slope of Lake Kinneret relationship was at least 50% higher than that of the fishponds.

Table 2. Comparison of regression statistics for several studies in which total chlorophyll was regressed against the predictor - reference peak height near 700 nm above baseline, from 670 nm to 750 nm ($RLH_{670-750}$): $Chl = a + b RLH_{670-750}$; $r^2$ is determination coefficient.

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>a</th>
<th>b</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Kinneret</td>
<td>March and April 1993</td>
<td>1.77</td>
<td>40.8</td>
<td>0.96</td>
</tr>
<tr>
<td>Lake Kinneret</td>
<td>February 1994</td>
<td>2.27</td>
<td>43.4</td>
<td>0.94</td>
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<td>Haifa Bay, Israel</td>
<td>May 1994 and June 1995</td>
<td>4.90</td>
<td>47.2</td>
<td>0.93</td>
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<tr>
<td>Carter Lake, USA</td>
<td>April 1995 to April 1996</td>
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<td>31.8</td>
<td>0.83</td>
</tr>
<tr>
<td>Waste water ponds, Israel</td>
<td>May 1996</td>
<td>1.20</td>
<td>18.0</td>
<td>0.88</td>
</tr>
<tr>
<td>Iowa lakes, USA</td>
<td>September 1996</td>
<td>2.30</td>
<td>36.0</td>
<td>0.86</td>
</tr>
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</table>
Fig. 6. Validation of the reflectance ratio algorithm, \( R_{700}/R_{570} \), for estimation of Chl concentration in Lake Kinneret. Chl concentrations were predicted by ratio \( R_{700}/R_{570} \) measured in April 1993. Relationship \( R_{700}/R_{570} \) vs. Chl (solid line), obtained in March 1993, was used to calculate predicted Chl. Then, predicted Chl was compared with measured Chl concentrations (insert). Error of Chl prediction, determined as root-mean square deviation of predicted from measured Chl values, did not exceed 18 mg m\(^{-3}\). The slope of the relationship \( R_{700}/R_{570} \) vs. Chl changed in various experiments (see Figs 5 and 6). In the cases presented herein, slope of Lake Kinneret relationship was at least 50% higher than that of the fishponds.

Relationships Chl vs. reflectance line height were in agreement (they ranged from 31.8 to 47.2 - Table 2). Minimal b value (31.8) was found for Carter Lake, Nebraska in a full annual cycle. Taking into account the extremely diverse trophic status of these water bodies, the existence of robust relationship between Chl concentration and suggested variables of reflectance was indicated.

Table 2. Comparison of regression statistics for several studies in which total chlorophyll was regressed against the predictor - reference peak height near 700 nm above baseline, from 670 nm to 750 nm (RLH\(_{670-750}\)): Chl = a + b RLH\(_{670-750}\); \( r^2 \) is determination coefficient.

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The suitability of these algorithms for estimating the density of phytoplankton in water bodies dominated by cyanobacteria is of great importance, considering the significance of these algal as a potential environmental hazard.

**Future options: Satellite borne sensors**

A major, unresolved issue is determining whether our findings from high spectral resolution radiometer measurements, obtained at close range, can be applied to satellite sensors with limited spectral resolution. Global maps of algal density (i.e., Chl a) in the oceans were achieved using wide band sensors and/or with a small number of narrower channels appropriate for phytoplankton sensing (i.e. CZCS and SeaWiFS). We infer from our work that the spectral requirements for Chl estimation are quite restricted, and use of an instrument with several narrow (10-20 nm) spectral channels in the red and near infra-red ranges should be sufficient. We suggest that an optimum configuration would include channels centered at 600, 626, 650 nm (accessory chlorophylls), 670 nm (Chl absorption and reference for baseline), 685 nm (Chl fluorescence), 700 nm (NIR peak position), and 750 nm (reference for baseline). In the near future, narrow band, satellite sensors will offer better capability for the detection of phytoplankton pigments: MERIS (ESA) and MODIS (NASA) aimed to monitor photosynthetic pigments in terrestrial vegetation and in aquatic environments. The spectral channels of these sensors (especially of MERIS) coincide to a certain degree with the significant spectral features of water constituents in inland waters (Fig. 8). These sensors include spectral channels for atmospheric corrections that are mandatory for monitoring inland water quality from space.

In order to utilize the satellite acquired data for water quality monitoring, several steps of operation are needed:

- adjustment of algorithms for Chl estimation, developed by the use of high-resolution spectroradiometers at ground level, to the capabilities offered by satellite-carried sensors;
- establishment of a routine for satellite image acquisition, processing and analysis, including geometrical and atmospheric corrections of the images, and selection of the relevant optical information;
- validation of the satellite data by ground observations in aquatic ecosystems of varying productivity.

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**References**

Fig. 8. Typical reflectance spectrum of productive inland waters and the location of the bands of MERIS system.


