

## 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

---

### Authors' addresses:

A.A. Gitelson, J. Blaustein Institute for Desert Research, Ben-Gurion University of the Negev, Sede Boker 84990, Israel. gitelson@bgumail.bgu.ac.il. Y.Z. Yacobi, Israel Oceanographic & Limnological Research, Yigal Allon Kinneret Limnological Laboratory, Israel. J.F. Schalles, Department of Biology, Creighton University, Omaha, NE 68178-0103, USA. D.C. Rundquist, Center for Advanced Land Management Information Technologies, School of Natural Resource Sciences, University of Nebraska-Lincoln, Lincoln, NE 68588-0517, USA. L. Han, Department of Geography, University of Alabama, Tuscaloosa, AL, USA. R. Stark, Department of Geology and Environmental Sciences, Ben-Gurion University of the Negev, Beer Sheva, Israel. D. Etzion, Department of Geophysics and Planetary Sciences, Tel Aviv University, Ramat Aviv, Israel.

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  $\alpha$  (Chl), a signature substance of phytoplankton is mostly below  $1 \text{ mg m}^{-3}$  (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  $5 \text{ mg m}^{-3}$  to hundreds of  $\text{mg m}^{-3}$  (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 (POLLINGER 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 1.** Water bodies studied, period of observations, range of chlorophyll *a* variation and dominant phytoplankton.

Site	Period	Chlorophyll <i>a</i> ( $\text{mg m}^{-3}$ )	Dominant phytoplankton
Lake Kinneret	winter-spring	2.4-330	<i>Peridinium gatunense</i>
Lake Kinneret	summer-fall	3.8-26	Chlorophytes
Iowa Lakes, USA	summer	2.0-55	Diatoms
Carter Lake, USA	year round	20-280	<i>Anabaena</i> sp.
Fish ponds, northern Israel	winter-spring	2.1-674	<i>Microcystis aeruginosa</i>
Wastewater ponds, Israel	spring-summer	69-2700	Chlorophytes
Haifa Bay, Israel	spring-summer	1-70	Dinoflagellates, diatoms

water ( $L_w$ ) and of a reference plate ( $L_{ref}$ ) were measured using high spectral resolution spectroradiometers: 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.

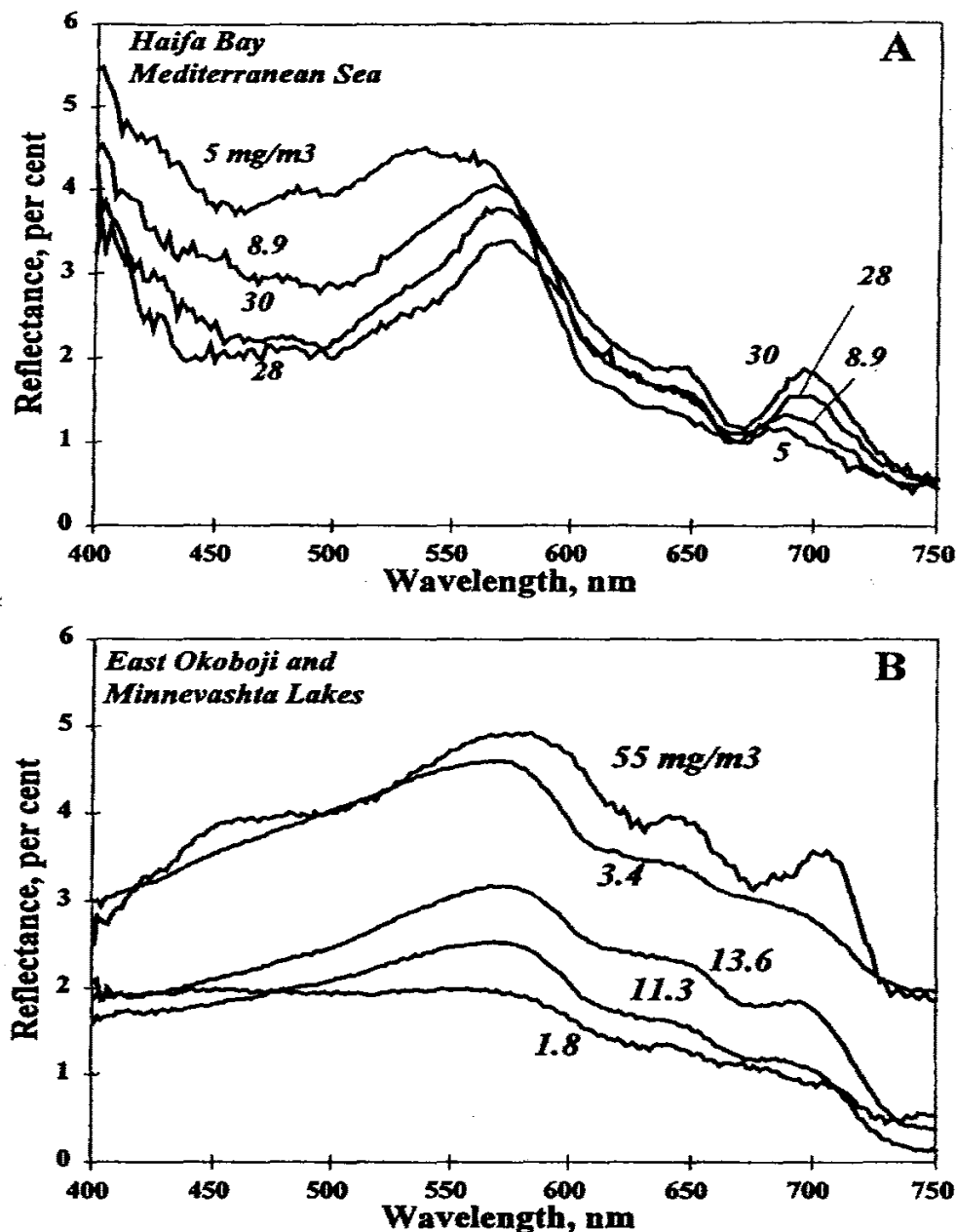
## Reflectance spectra

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 particular 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 oligotrophic 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  $\beta$ -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  $20 \text{ mg m}^{-3}$ , 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.

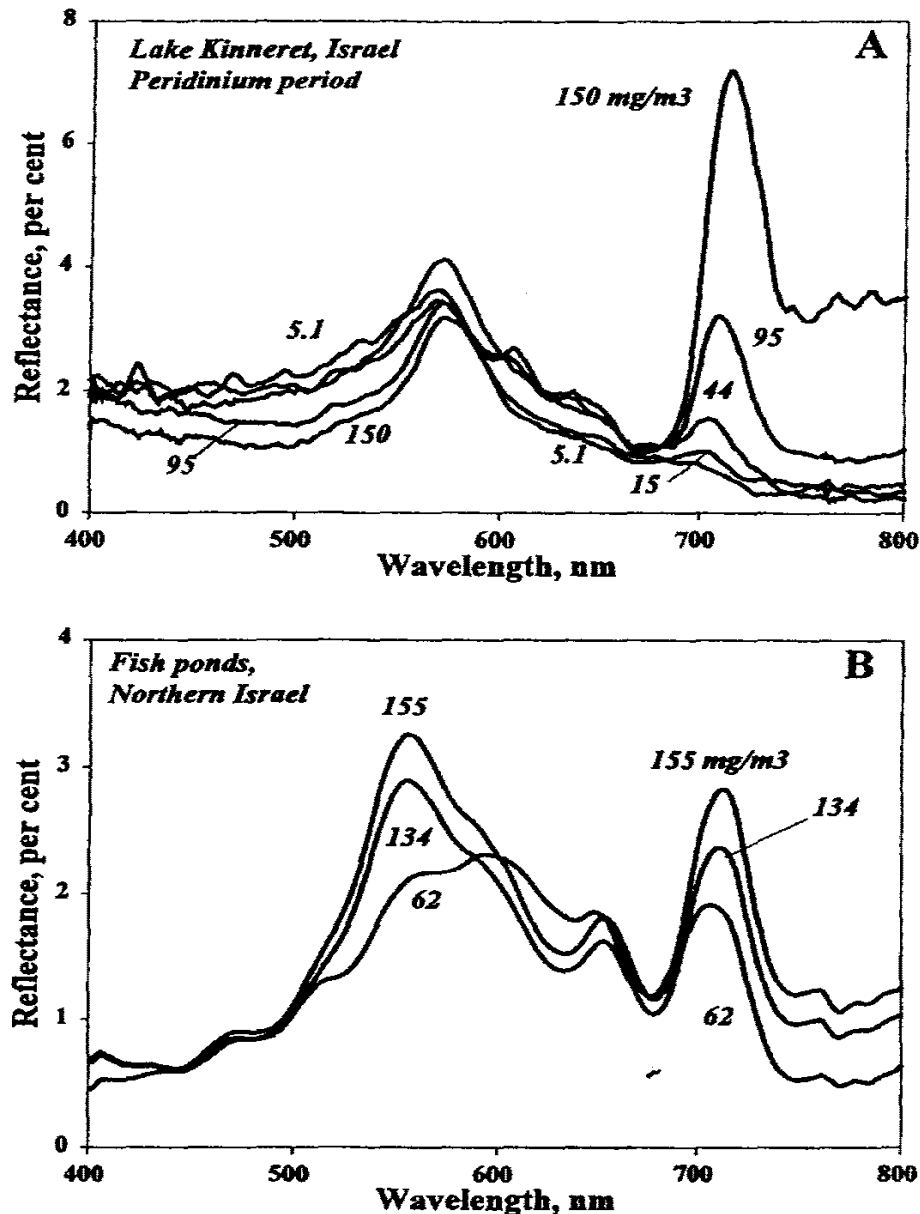


Fig. 2. Reflectance spectra of aquatic systems with moderate to high Chl concentrations. (a) Lake Kinneret, February 1994. In the range 400 to 550 nm, absorption by pigments was so strong that it was hardly to distinguish between spectra with Chl ranging between 5 and 150 mg m<sup>-3</sup>. Magnitude 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<sup>-3</sup> (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 phycobillins (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  $> 20 \text{ mg m}^{-3}$  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  $15\text{--}20 \text{ mg m}^{-3}$  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  $< 10 \text{ mg m}^{-3}$ ; 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.

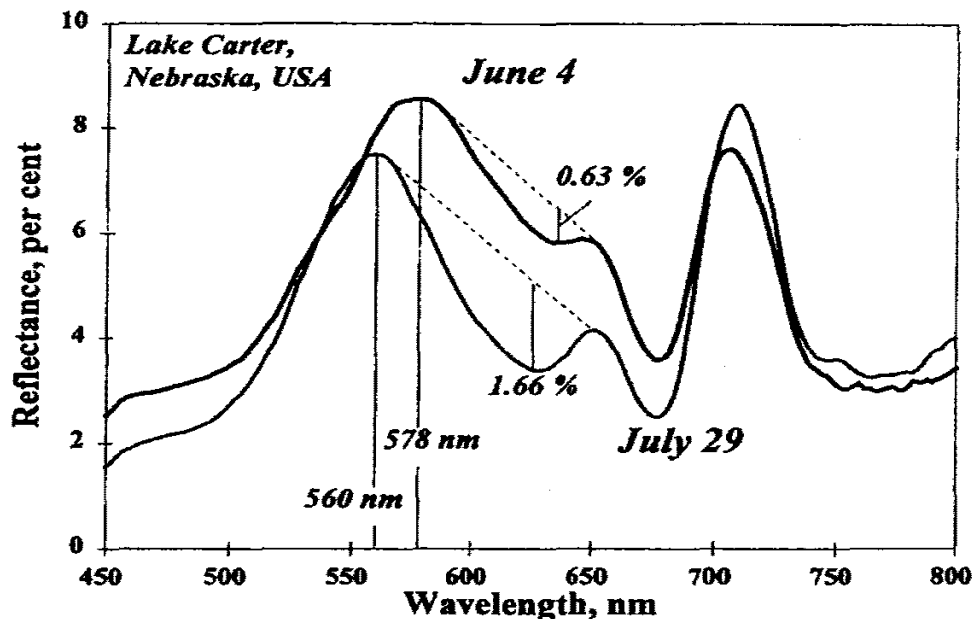
## Algorithm construction and validation

**Low Chl concentration.** In productive, turbid waters with Chl concentrations below  $20 \text{ mg m}^{-3}$ , 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  $10 \text{ mg m}^{-3}$  (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  $1 \text{ mg m}^{-3}$ ; in Iowa lakes in the range of Chl concentration from 2 to  $55 \text{ mg m}^{-3}$ , the estimation error was  $7.8 \text{ mg m}^{-3}$ .

**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  $\text{Chl} > 15\text{--}20 \text{ mg m}^{-3}$ .

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  $180\text{--}200 \text{ mg m}^{-3}$ , 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



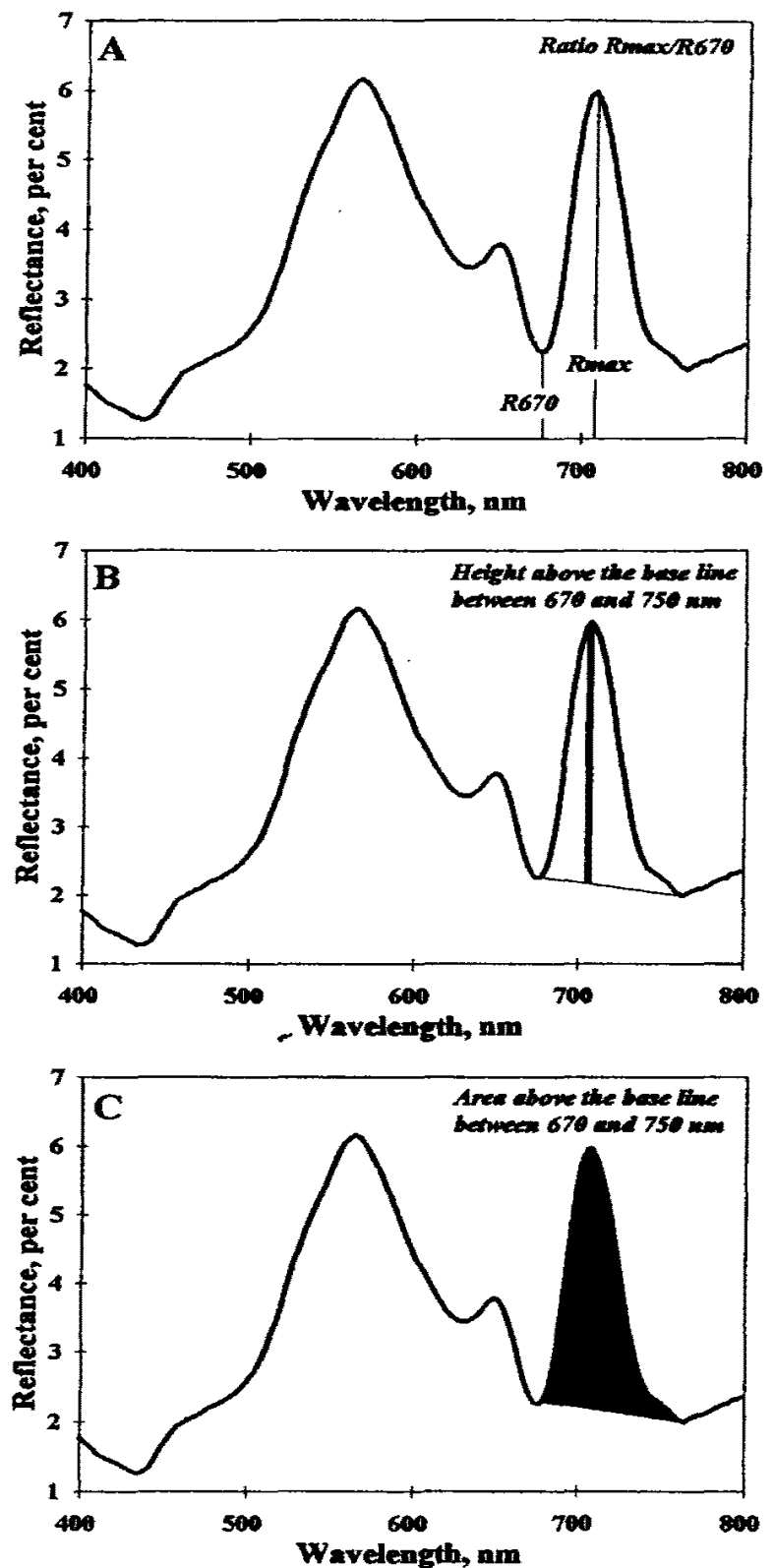
**Fig. 3.** Demonstration of accessory pigment effects on reflectance spectra. Two representative spectra from Carter Lake for June 4 and July 29, 1996. Chl concentrations were almost the same, but on July 29, phycocyanin (PC) concentration was much higher. As a result of higher PC concentration, the 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  $18 \text{ mg m}^{-3}$  (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  $> 20 \text{ mg m}^{-3}$ ,  $R_{670}$  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.

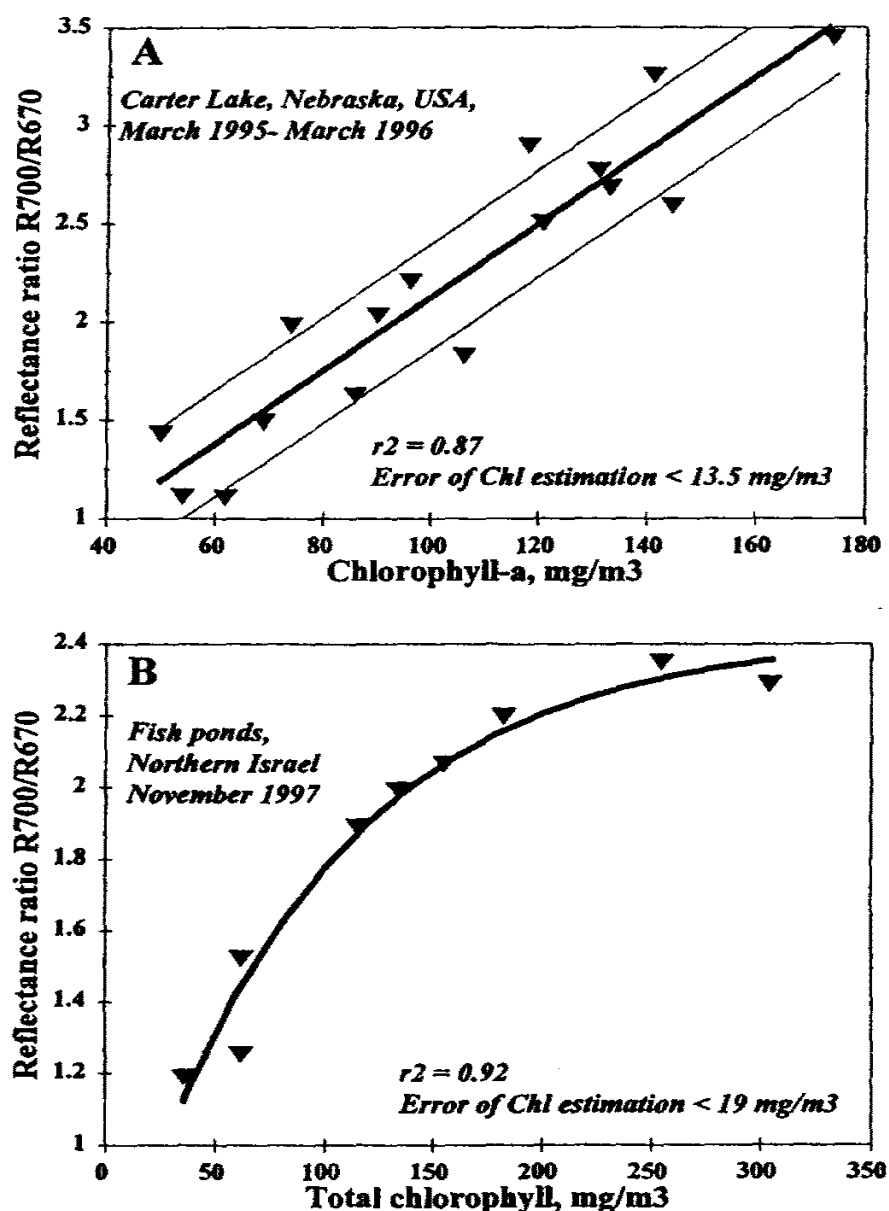
The regression of reflectance height at 700 nm above the baseline from 670 to 750 nm (Fig. 4b), as well as area above this baseline (Fig. 4c), and the position of the NIR peak (GITELSON





**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  $\alpha$  concentrations yielded high correlation coefficients, always  $r^2 > 0.90$  (GITELSON et al. 1994a, YACOBI et al. 1995). The developed algorithms were validated by



**Fig. 5.** Validation of the reflectance ratio algorithm,  $R_{700}/R_{670}$ , for estimation of Chl concentration. (a) Carter Lake, March 1995-March 1996. The solid line represents the best-fit function; the dotted lines represent standard error of chlorophyll estimation; (b) Fishponds in the Jordan Valley, Israel, February 1998. For Chl < 180 mg m<sup>-3</sup>, the relationship ratio vs. Chl was linear, and then leveled off.

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<sup>-3</sup>) 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-

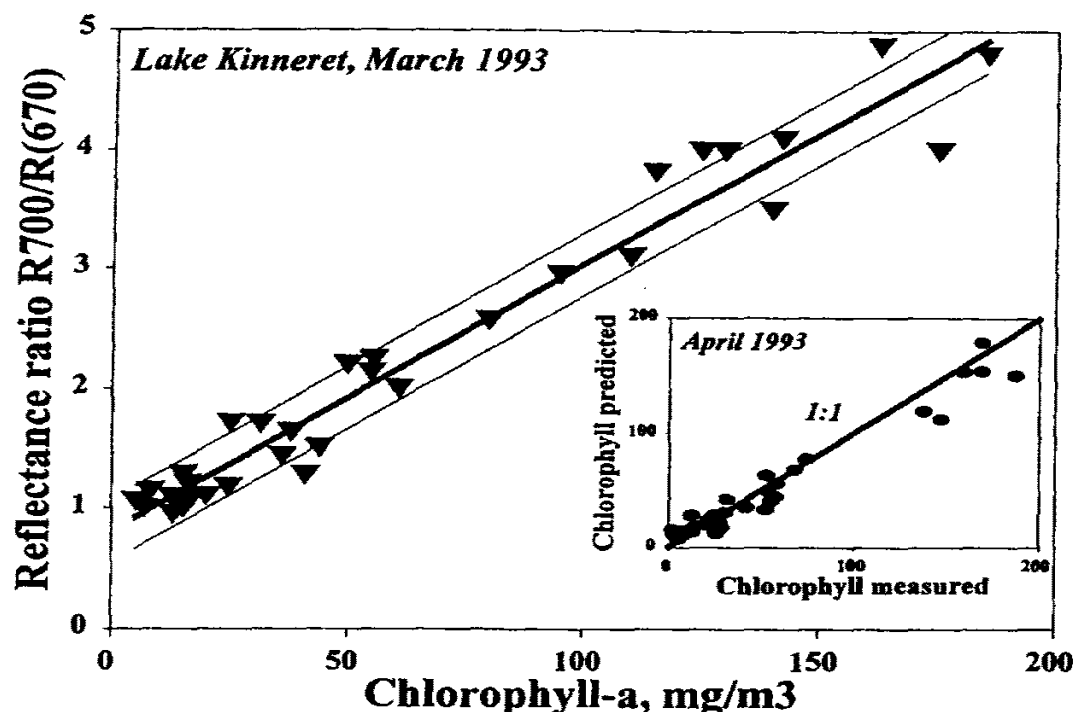


Fig. 6. Validation of the reflectance ratio algorithm,  $R_{700}/R_{670}$ , for estimation of Chl concentration in Lake Kinneret. Chl concentrations were predicted by ratio  $R_{700}/R_{670}$  measured in April 1993. Relationship  $R_{700}/R_{670}$  vs. Chl (solid line), obtained in March 1993, was used 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  $18 \text{ mg m}^{-3}$ . 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.

tionships 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 ( $RLH_{670-750}$ ):  $\text{Chl} = a + b \text{RLH}_{670-750}$ ;  $r^2$  is determination coefficient.

Site	Period	a	b	$r^2$
Lake Kinneret	March and April 1993	1.77	40.8	0.96
Lake Kinneret	February 1994	2.27	43.4	0.94
Haifa Bay, Israel	May 1994 and June 1995	4.90	47.2	0.93
Carter Lake, USA	April 1995 to April 1996	6.20	31.8	0.83
Waste water ponds, Israel	May 1996	1.20	18.0	0.88
Iowa lakes, USA	September 1996	2.30	36.0	0.86

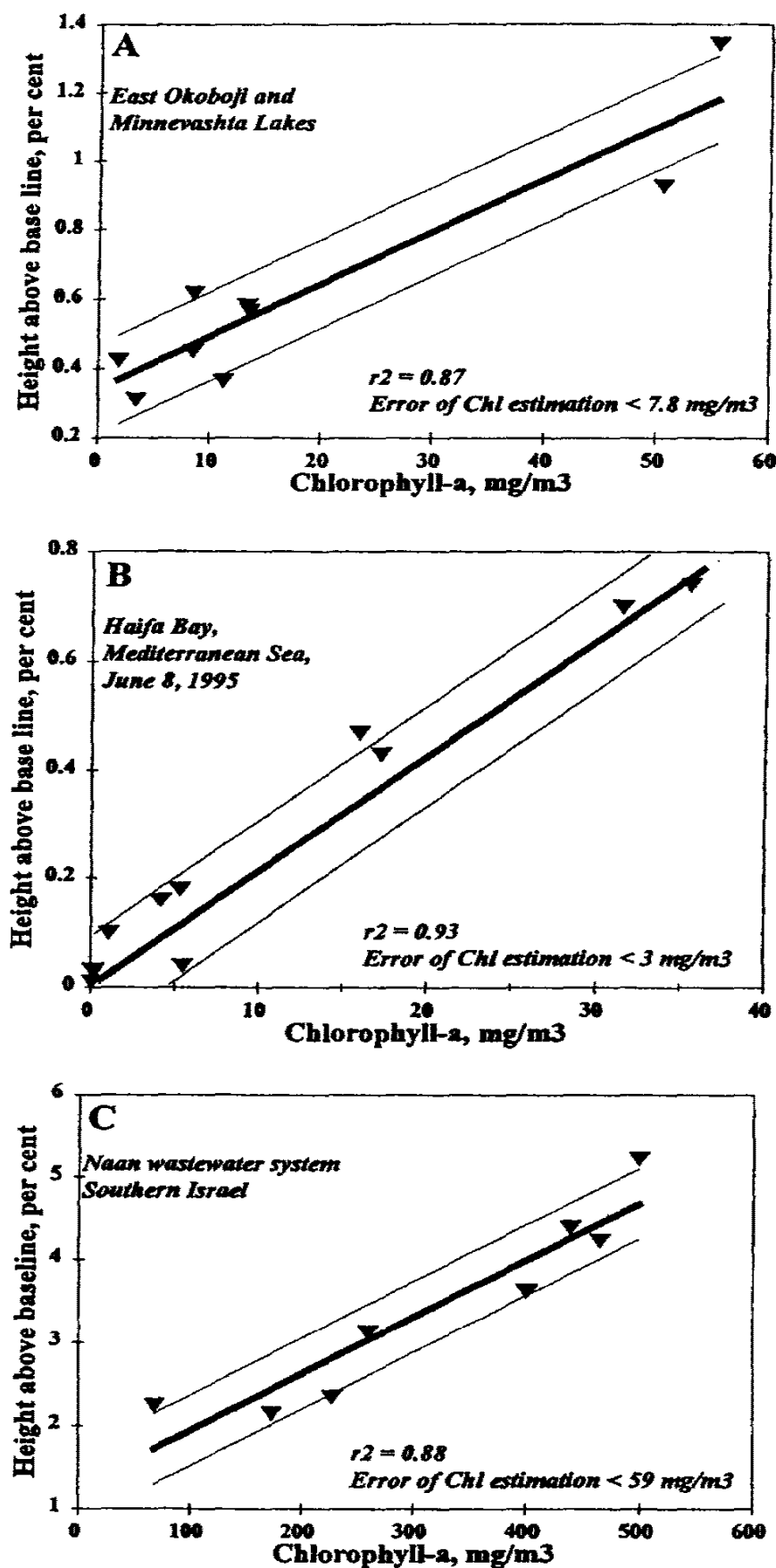


Fig. 7. Validation of the algorithm, height of the peak near 700 nm above a baseline drawn from 670 nm to 750 nm, for estimation of Chl concentration. (a) Lakes in north-western Iowa, USA, September 1996; (b) Haifa Bay, southeastern Mediterranean Sea, June 1995; (c) Waste water ponds, Israel, May 1998. The difference in Chl concentrations between the extremes (Fig 7a and 7c) was at least ten-fold. Nevertheless, in all the systems examined in our studies, we found a linear relationship between the height above the base line and Chl concentration. Note, however, that the coefficients of the relationships changed between experiments (Table 2).

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 base-line), 685 nm (Chl fluorescence), 700 nm (NIR peak position), and 750 nm (reference for base line). 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.

### **Acknowledgments**

This work was supported by grants from the Israel National Academy of Sciences and Humanities, Water Commissioner's Office, Israel Ministry of Science and from the US-Israel Binational Science Foundation (BSF Grant N. 94-00087/1).

### **References**

- BERMAN, T., YACOBI Y.Z. & POLLINGER, U. (1992): Lake Kinneret phytoplankton: stability and variability during twenty years (1970-1989). – *Aquat. Sci.* 54: 104-127.

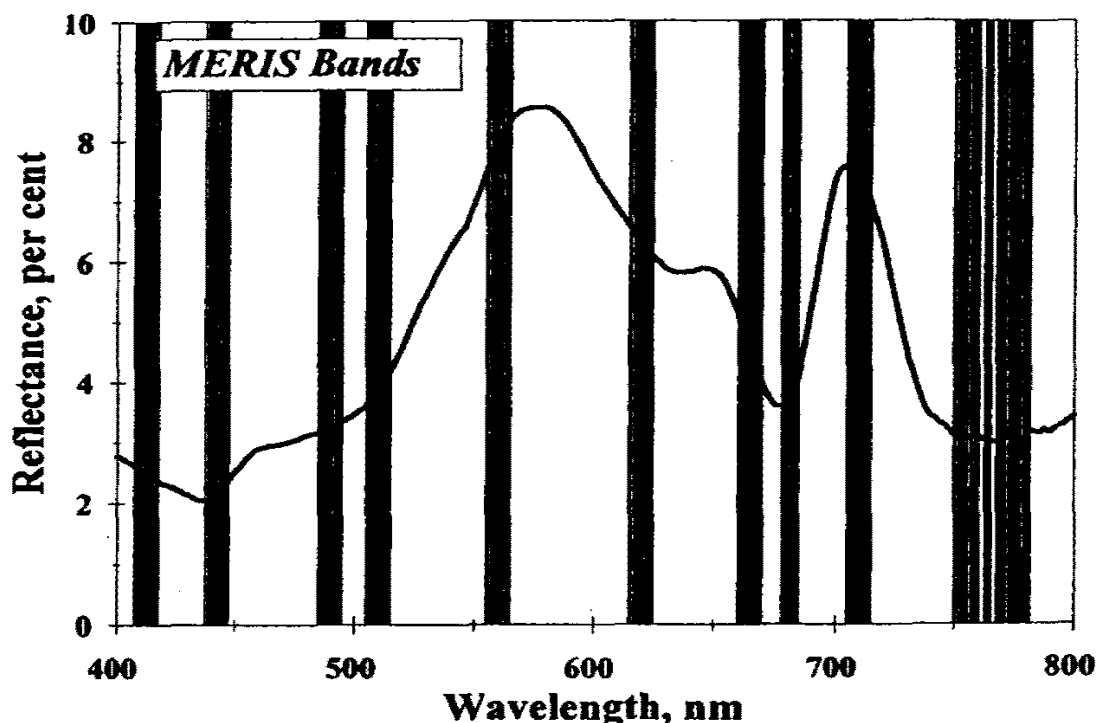


Fig. 8. Typical reflectance spectrum of productive inland waters and the location of the bands of MERIS system.

- BERMAN, T., STONE, L., YACOBI, Y.Z., SCHLICHTER, M., NISHRI, A. & POLLINGER, U. (1995): Primary production in Lake Kinneret: A long term record 1972-1993). – *Limnol. Oceanogr.* **40**: 1064-1076.
- BUKATA, R.P., JEROME, H.H., KONDRATYEV, K.Y. & POZDNYAKOW, D.V. (1995): *Optical Properties and Remote Sensing of Inland and Coastal Waters*. – CRC Press, Boca Raton, New York, London, Tokyo, 362p.
- DEKKER, A. (1993): Detection of the optical water quality parameters for eutrophic waters by high resolution remote sensing. – Ph.D. Thesis, Free University, Amsterdam, The Netherlands, 212 p.
- DOERFFER, R. (1981): Factor Analysis in Ocean Color Interpretation – In: GOWER, J.F.R. (ed): *Oceanography from Space*, pp. 339-345, Plenum Press, New York.
- FISCHER, J. & KRONFELD, V. (1990): Sun-stimulated chlorophyll fluorescence. 1: Influence of oceanic properties. – *Int. J. Remote Sensing* **11**: 2125-2147.
- GKSS (1986): The use of chlorophyll fluorescence measurements from space for separating constituents of sea water. – ESA Contract No. RFQ3-5059/84/NL/MD, Vol II, Appendices, GKSS Research Centre.
- GITELSON, A. (1992). The peak near 700 nm on reflectance spectra of algae and water: relationships of its magnitude and position with chlorophyll concentration. – *Int. J. Remote Sensing* **13**: 3367-3373.
- (1993): The nature of the peak near 700 nm on the radiance spectra and its application for remote estimation of phytoplankton pigments in inland waters. – *Optical Engineering and Remote Sensing, SPIE* 1971, pp. 170-179.
- GITELSON, A., NIKANOROV, A.M., SABO, G. & SZILAGYI, F. (1986): Etude de la qualite des eaux de surface par teledetection. – *IAHS Publications* **157**: 111-121.
- GITELSON, A., GARBUZOV, G., SZILAGYI, F., MITTENZWEY, K.H., KARNIELI, A. & KAISER, A. (1993a): Quantitative remote sensing methods for real-time monitoring inland water quality. – *Int. J. Remote Sensing* **14**: 1269-1295.
- GITELSON, A., SZILAGYI, F. & MITTENZWAY, K. (1993b): Improving quantitative remote sensing for monitoring of inland water quality. – *Water Res.* **7**: 1185-1194.

- GITELSON, A., MAYO, M. & YACOBI, Y.Z. (1994a): Signature analysis of reflectance spectra and its application for remote observations of the phytoplankton distribution in Lake Kinneret. – *Mesures Physiques et Signatures en Teledetection*. ISPRS 6th International Symposium, Val d'Isere, France, pp. 277-283.
- GITELSON, A., MAYO, M., YACOBI, Y.Z., PARPAROV, A. & BERMAN, T. (1994b): The use of high spectral radiometer data for detection of low chlorophyll concentrations in Lake Kinneret. – *J. Plankton Res.* **16**: 993-1002.
- GITELSON, A., LAORAWAT, S., KEYDAN, G.P. & VONSHAK, A. (1995): Optical properties of dense algal cultures outdoors and its application to remote estimation of biomass and pigment concentration. – in: *Spirulina platensis*. – *J. Phycology* **31**: 828-834.
- GITELSON, A., YACOBI, Y.Z., KARNIELI, A. & KRESS, N. (1996): Reflectance spectra of polluted marine waters in Haifa Bay, Southeastern Mediterranean: Features and application for remote estimation of chlorophyll concentration. – *Israel J. Earth Sci.* **45**: 127-136.
- GITELSON, A.A., STARK, R. & DOR, I. (1997): Quantitative near-surface remote sensing of wastewater quality in oxidation ponds and reservoirs: A case study of the Naan system. – *Water Environ. Res.* **69**: 1263-1271.
- GOODIN, D.G., HAN, L., FRASER, R.N., RUNDQUIST, D.C., STEBBINS, W.A. & SCHALLES, J.F. (1993): Analysis of suspended solids in water using remotely sensed high resolution derivative spectra. – *Photogram. Eng. Rem. Sens.* **59**: 505-10.
- GORDON, H. & MOREL, A. (1983): Remote Assessment of Ocean Color for Interpretation of Satellite Visible Imagery. A Review. – Springer-Verlag, New York, 114 p.
- GOWER, J.F.R. (1980): Observations of in-situ fluorescence of chlorophyll- $\alpha$  in Saanich Inlet. – *Boundary Layer Meteorol.* **18**: 235-245.
- HAN, L., RUNDQUIST, D.C., LIU, L.L., FRASER, R.N. & SCHALLES, J.F. (1994): The spectral responses of algal chlorophyll in water with varying levels of suspended sediment. – *Int. J. Remote Sensing* **15**: 3707-18.
- JONES, J.R. & BACHMANN, R.W. (1974): Limnological features of some northwestern Iowa lakes. – *Proc. Iowa Acad. Sci.* **81**: 158-163.
- KIRK, J.T.O. (1994): Light and Photosynthesis in Aquatic Ecosystems. – Cambridge University Press, 509 p.
- KISHINO, M., SUGIHARA, S. & OKAMI, N. (1986): Theoretical analysis of the in-situ fluorescence of chlorophyll-a on the underwater spectral irradiance. – *Bulletin de la Societe Franco-Japonaise d'Océanographie* **24**: 130-138.
- MILLIE, D.F., BAKER, M.C., TUCKER, C.S., VINYARD, B.T. & DIONIGI, C.P. (1992): High-resolution airborne remote sensing of bloom-forming phytoplankton. – *J. Phycol.* **28**: 281-90.
- MITTENZWEY, K.-H. & GITELSON, A. (1988): In-situ monitoring of water quality on the basis of spectral reflectance. – *Int. Revue Ges. Hydrobiol.* **73**: 61-72.
- MITTENZWEY, K.-H., ULLRICH, S., GITELSON, A. & KONDRATÉV, K.YA., (1992): Determination of chlorophyll- $\alpha$  of inland waters on the basis of spectral reflectance. – *Limnol. Oceanogr.* **37**: 147-149.
- MOREL, A. & PRIEUR, L. (1977): Analysis of variation in ocean color. – *Limnol. Oceanogr.* **22**: 709-22.
- NEVILLE, R.A. & GOWER, J.F.R. (1977): Passive remote sensing of phytoplankton via chlorophyll-a fluorescence. – *J. Geophys. Res.* **82**: 3487-3493.
- ORON, G. & GITELSON, A. (1996): Real-time quality monitoring by remote sensing of contaminated water bodies: waste stabilization pond effluent. – *Water Res.* **30**: 3106-3114.
- QUIBELL, G. (1992): Estimation chlorophyll concentrations using upwelling radiance from different freshwater algal genera. – *Int. J. Remote Sensing* **13**: 2611-2621.
- POLLINGER, U. (1986): Phytoplankton periodicity in a subtropical lake (Lake Kinneret, Israel). – *Hydrobiol.* **138**: 127-138.
- RUNDQUIST, D.C., SCHALLES, J.F. & PEAKE, J.S. (1995): The response of volume reflectance to manipulated algal concentrations above bright and dark bottoms at various depths in an experimental pool. – *Geocart Int.* **10**: 5-14.

- RUNDQUIST, D.C., HAN, L., SCHALLES, J.F. & PEAKE, J.S. (1996): Remote measurement of algal chlorophyll in surface waters: the case for the first derivative of reflectance near 690 nm. – *Photogram. Eng. Rem. Sens.* **62**: 195-200.
- SCHALLES, J.F. GITELSON, A., YACOBI, Y.Z. & KROENKE, A.E. (1998): Chlorophyll estimation using whole seasonal, remotely sensed high spectral-resolution data for an eutrophic lake. – *J. Phycol.* **34**: 383-390.
- SCHALLES, J.F., SCHIEBE, F.R., STARKS, P.J. & TROEGER, W.W. (1997): Estimation of algal and suspended sediment loads (singly and combined) using hyperspectral sensors and integrated mesocosm experiments. – *Proc. of the fourth International Conference on Remote Sensing of Marine and Coastal Environments*. 17-19 March 1997, Orlando, Florida, USA. Environmental Research Institute of Michigan, Ann Arbor, MI, Vol. I: 247-258.
- STARK, R., GITELSON, A. & ORON, G. (1996): Quantitative remote sensing for real-time monitoring polluted water bodies quality. – *5th International Conference on Wetland Systems for Water Pollution Control*, Vienna, September 15-19, 1996, **2**: 28/1-4.
- YACOBI, Y.Z., GITELSON, A. & MAYO, M. (1995): Remote sensing of chlorophyll in Lake Kinneret using high spectral resolution radiometer and Landsat TM: Spectral features of reflectance and algorithm development. – *J. Plankton Res.* **17**: 2155-2173.
- VOS, W.L., DONZE, M. & BUETEVELD, H. (1986): On the reflectance spectrum of algae in water: The nature of the peak at 700 nm and its shift with varying concentration. – *Communication of Sanitary Engineering and water Management*, Delft, The Netherlands, Technical Report, 86-22.