INT. J. REMOTE SENSING, 1995, VOL. 16, NO. 1, 175–182

Chlorophyll distribution in Lake Kinneret determined from Landsat Thematic Mapper data

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(Received 14 October 1993; in final form 20 April 1994)

Abstract. Chlorophyll distribution in Lake Kinneret was estimated at a time of low chlorophyll concentrations (3–7 mgm^{-3}). Landsat Thematic Mapper (TM) data were acquired three days after the acquisition of high spectral resolution radiometric measurements in the range 400 to 750 nm, chlorophyll and suspended matter concentrations, and Secchi disk transparency at 22 stations. The radiometric data were used to create an algorithm for estimation of chlorophyll concentration from the TM data. The radiance in channel TM3 (620–690 nm) was primarily dependent upon non-organic suspended matter concentration. Radiance in this channel was substracted from radiance in TM1 (450–520 nm) to correct for the additional radiance caused by scattering of non-pigmented suspended particles and (TM1 − TM3)/TM2 was found to be a useful index for estimating chlorophyll concentration. The concentrations calculated from atmospherically corrected TM data were compared to chlorophyll extracted from lake water samples. The estimation error of chlorophyll concentration was less than 0·85 mgm^{-3}.

1. Introduction

Lake Kinneret is the only large freshwater body in Israel. It supplies approximately one third of the national water demand, and has other uses such as recreation and commercial fishing. Fluctuation in the water level is currently a major concern for water policy makers in Israel, as the long-term impact of these changes on water quality is largely unknown (Berman *et al.* 1992). Algal density is a key water quality variable in the lake monitoring program. The distribution of algae in the lake is irregular, both spatially and temporally, and this causes severe sampling problems. An effective method for monitoring the distribution of algae in the lake could be remote sensing. Often, even a few images are useful as aids in the design or

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improvement of point sampling programmes through the location of optimum sampling stations.

The spatial resolution of satellite-sensor derived images has increased during the last decade. As a result of its high spatial resolution (30 m), the Landsat TM sensor is suitable for investigation of inland waters such as Lake Kinneret. TM data for chlorophyll (Chl) estimation in inland waters have been used by several groups (Dekker *et al.* 1992, Gitelson *et al.* 1986, Jacquet and Zang 1989, Reardon and McGarrigle 1989, Ritchie *et al.* 1990). A review of TM use for inland waters has been published by Dekker (1993). Statistical techniques for the derivation of the correlation between spectral bands and Chl concentration have been the most common approach. Though limited in their universal application, empirically derived algorithms can provide adequate estimation of Chl concentration. For successful extrapolation to conditions other than those under which these algorithms are calibrated, adjustment of their parameters is required. In particular, a problem is posed by the relatively low Chl concentration combined with a background of quite high and variable non-organic suspended matter (SM), occurring in Lake Kinneret in summer–autumn periods (Berman *et al.* 1992).

This research follows two separate but integrated tasks. The first phase of the study deals with the analysis of reflectance spectra. Optical models of the lake relating the reflectance of the water to constituent concentrations in surface waters were created. This stage allowed the development of algorithms for precise Chl estimation using Chl fluorescence as measured in the red region of the spectrum (Gitelson *et al.* 1994). The second task, discussed in this Letter, was to use the Landsat TM data for monitoring Chl in Lake Kinneret.

2. Methods

Twenty-two locations were sampled on 26 and 27 October 1992. They were located in the northern part of the lake, where the water depth ranged from 8 to 43 m. The sampling scheme was intended to cover as high a variation of Chl and SM concentrations as possible.

At every sampling station, the upward radiance, L_u, above the water surface, and (indirectly) the downward radiance, L_d, were measured (with the aid of a standard reflectance white plate) with a LI-1800 radiometer in the region 400–750 nm with spectral resolution of 2 nm. The measurements were taken using a telescope with a field of view of 15°. Each observed upward radiance spectrum was divided by the appropriate downward radiance spectrum to give a reflectance as $R = L_u/L_d$.

Water was taken with a 51 Aberg–Rodhe sampler 0·0–0·5 m below surface and then Chl and SM concentrations were measured in the laboratory.

TM Landsat image 174/37 was acquired for 30 October 1992. The TM data were geometrically corrected to enable us to locate the sampling stations and extract radiometric data for validation. As a result of the procedure, every pixel in the image corresponded to a known location in the study area and the radiometric data for this location were examined. A 3×3 pixel window, centred on the sample point, was used to extract the digital numbers for each of the spectral bands. These data were then averaged for each sample point (Ritchie and Cooper 1987).

Atmospheric correction was carried out by means of an algorithm developed by Fraser *et al.* (1992). Input data for the correction consisted of the TM measured radiances, view and illumination directions, and the aerosol optical thickness that was derived from ground-measured values of solar transmission (Kaufman and

Fraser 1983). The output data of the procedure were the surface reflectances for corresponding points of the image.

The measurements of transmission of the direct sunlight were performed with a sunphotometer with eight spectral channels between 0·44 and 1·03 μm (Kaufman 1993). Measurements were taken when local sources of atmospheric pollution were not evident, so it is possible to assume that the atmosphere was spatially homogeneous across its lowest 2–4 km, where most of the tropospheric aerosols are present. The optical thickness was measured with an error of $\pm 0{\cdot}01$ to $\pm 0{\cdot}02$ (Kaufman 1993).

For destriping of the image, a two-dimensional Fourier transform filtering method was used. It was applied to the filtered Fourier images and the resulting lake image was substantially improved. An additional averaging (low-pass) filter was applied to remove random high-frequency noise (despeckling filter). The filtered lake image was converted from grey levels into shades of blue–cyan and planted in the surrounding land image using the land–sea mask mentioned earlier.

3. Results and discussion

The spatial distributions of Chl and SM was typical for Lake Kinneret at this time of the year (Berman *et al.* 1992). Chl ranged from 3·1 to 7·3 mgm^{-3} and SM ranged from 1·8 to 4·8 mgl^{-1}. The acquired reflectance spectra were all similar in general outline (figure 1). A low reflectance in the region 400–450 nm corresponded to Chl absorption. Then, reflectance increased steadily towards longer wavelength. The maximum, near 560–570 nm, was caused by minimum absorption by all phytoplankton pigments. Near 600 nm, the slope of spectral reflectance changed sharply owing to the spectral behaviour of the absorption coefficient of pure water. A minimum at 670–675 nm was recorded; it was evident for Chl $>$ 4 mgm^{-3}, and hardly distinguished for Chl $<$ 3·5 mgm^{-3}. A small reflectance peak around 690 nm (varying from 685 to 695 nm) was recorded in all spectra. At wavelengths greater

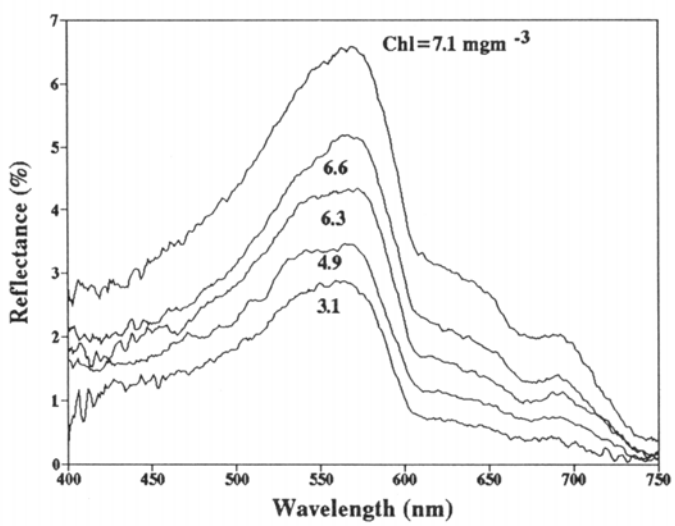

Figure 1. Reflectance spectra of Lake Kinneret. Chlorophyll concentrations measured *in situ* are indicated.

than 690–695 nm, the reflectance dropped sharply to a common reflectance value of about 0·1 per cent at 750 nm.

In this experiment, the correlation coefficient between Chl and SM, r^2, was less than 0·3. Therefore, it was not surprising that the correlation between the ratio $R(440)/R(550)$ and Chl was $r^2 < 0{\cdot}37$ (where $R(440)$ and $R(550)$ are the reflectances at the wavelengths 440 and 550 nm, respectively). A more precise Chl assessment ($r^2 > 0{\cdot}57$ within an estimation error $< 0{\cdot}79\,\mathrm{mgm}^{-3}$) was obtained using the reflectance ratio $R(520)/R(560)$.

To examine the accuracy of Chl estimation by using the blue/green ratio (TM1/TM2), the measured *in situ* reflectances were integrated on the bands TM1 (450–520) and TM2 (530–610). The regression between the reflectances calculated to simulate TM channels and the actual Chl measurements (in milligrams per cubic metre) yielded the function:

$$\mathrm{Chl} = 1{\cdot}43[R(450\text{–}520)/R(530\text{–}610)]^{-2{\cdot}6} \tag{1}$$

with $r^2 = 0{\cdot}47$. Therefore, the use of blue/green ratio algorithms (e.g. Gordon and Morel, 1983) is an inappropriate technique for Chl detection in Lake Kinneret.

To develop an algorithm for Chl estimation using TM data, the effect of SM on reflectance in the blue region of the spectrum had to be taken into consideration. As backscattering due to non-organic SM increases, the reflectance increases across the visible spectrum (Curran and Novo 1988, Lathrop *et al.* 1991, Ritchie *et al.* 1990). In this experiment, the concentration of dissolved organic matter was negligible (absorption coefficient of filtrate at 400 nm was less than $0{\cdot}1\,\mathrm{m}^{-1}$). In the region 620–690 nm, the contribution of the reflectance due to Chl fluorescence was less than 5 per cent of the total reflectance even for $\mathrm{Chl} = 7\,\mathrm{mgm}^{-3}$ (the maximal Chl concentration) and $\mathrm{SM} = 1{\cdot}8\,\mathrm{mgl}^{-1}$ (the minimal concentration). Therefore, the total reflectance in the region 620–690 nm depended primarily upon SM concentration. Support for this conclusion was provided by the close relationship between Secchi

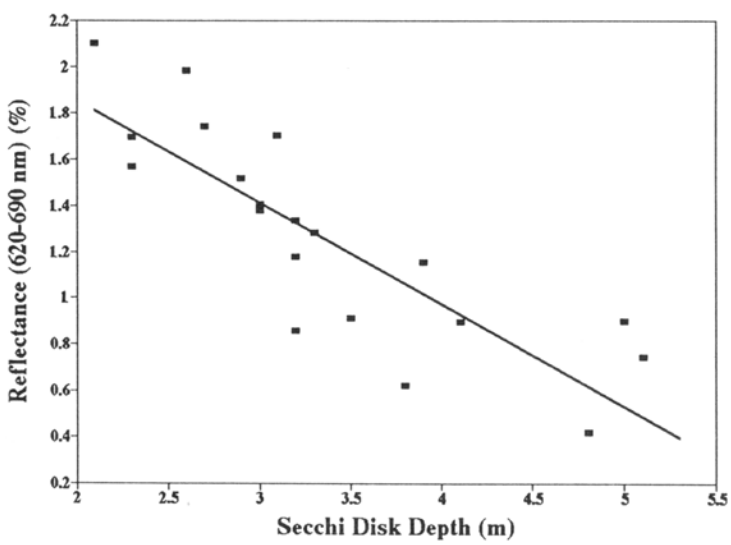

Figure 2. Comparison of the reflectance in the region 620–690 nm to Secchi disk depth.

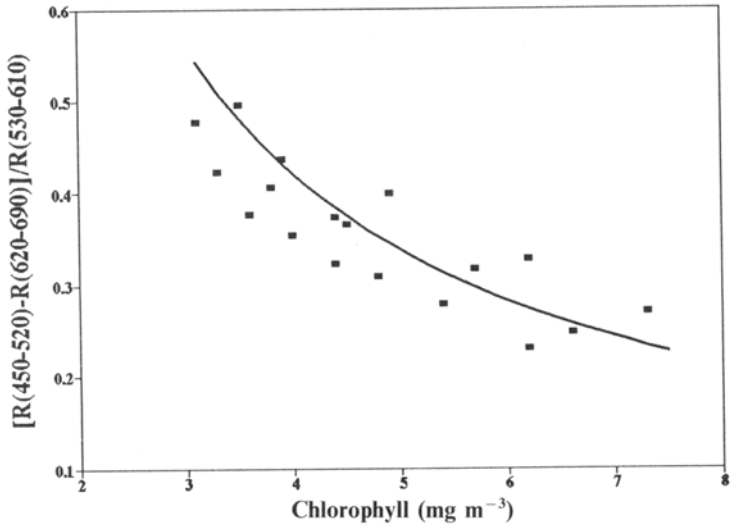

Figure 3. Reflectances integrated over the TM channels against chlorophyll concentration. The curve represents equation (2).

disk depth and the reflectance in the range of TM3 (620–690 nm), shown in figure 2. Hence, as a first order approach, radiance in TM3 can be used for subtraction from radiance in TM1 to correct for the additional radiance caused by scattering of non-organic SM.

Taking into account the above-mentioned consideration, the reflectances in the bands of TM were simulated using *in situ* reflectance measurements. The relationship between simulated reflectances and Chl concentrations (in milligrams per cubic

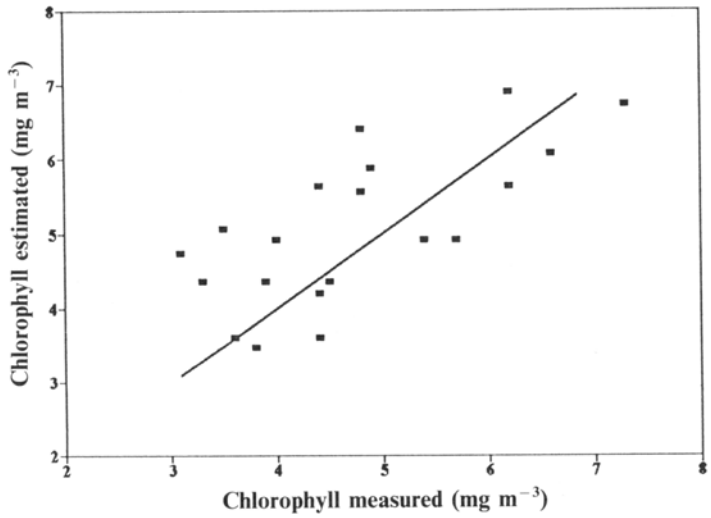

Figure 4. Chlorophyll concentration, calculated using equation (2) from atmospherically corrected TM data, plotted versus concentration measured in the laboratory.

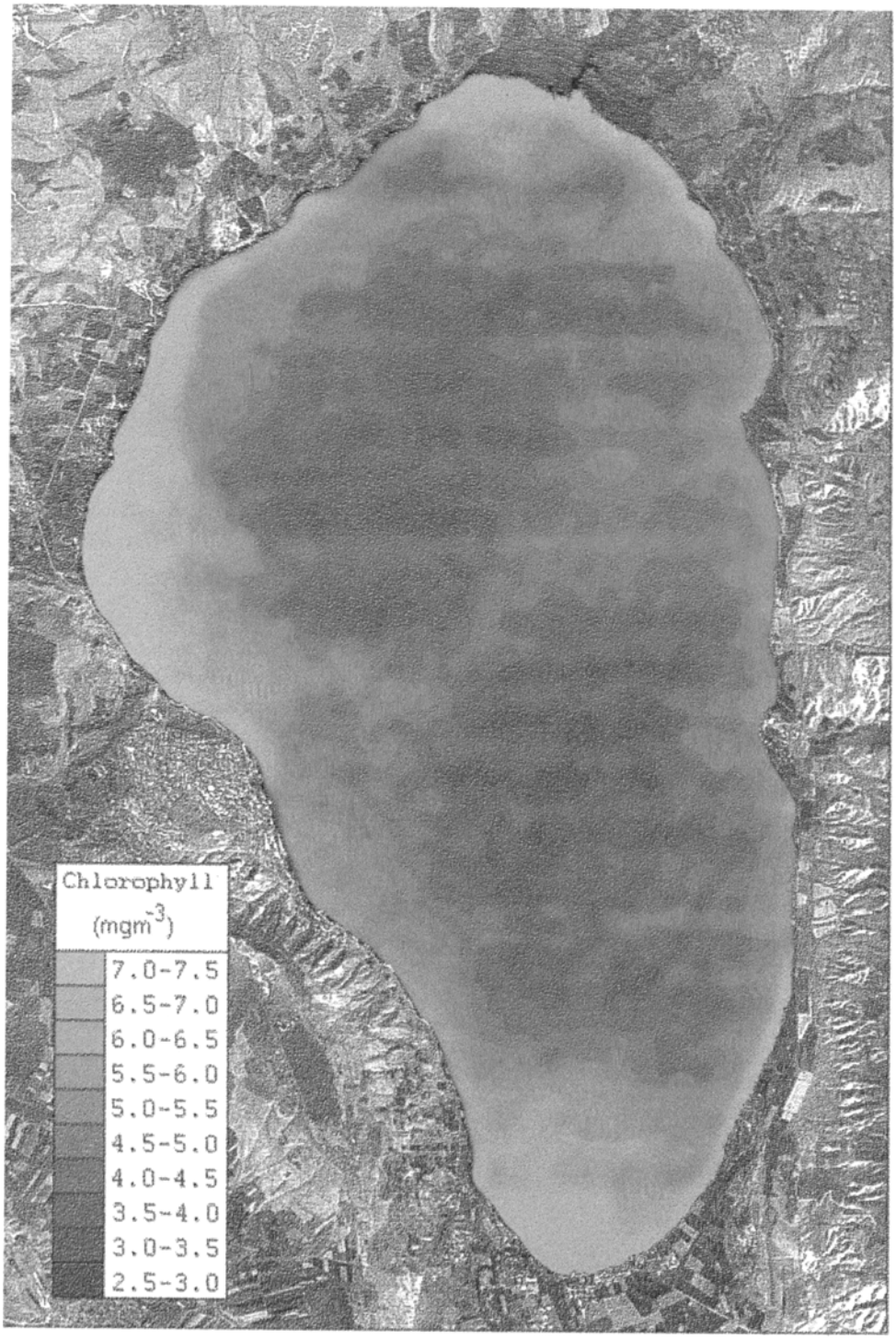

Figure 5. Map of chlorophyll distribution (in milligrams per cubic metre) in Lake Kinneret on 30 October 1992, produced by using equation (2) from atmospherically corrected TM data.

metre) was formulated as:

$$\mathrm{Chl} = 0{\cdot}164\{[R(450\text{–}520) - R(620\text{–}690)]/R(530\text{–}610)\}^{-0{\cdot}98} \quad (2)$$

with $r^2 = 0{\cdot}71$. This allowed the estimation of Chl concentration with an error of less than $0{\cdot}68\,\mathrm{mgm}^{-3}$ (figure 3).

Validation of the model by an independent dataset was carried out by applying equation (2), developed from the October 1992 data, to calculate the Chl concentration by using *in situ* reflectance measurements obtained in July 1993. The resulting calculated values were compared with the *in situ* Chl measurements in July 1993 at 25 stations. The estimation error of Chl concentration ranging from 3 to $10\,\mathrm{mgm}^{-3}$ was less than $0{\cdot}8\,\mathrm{mgm}^{-3}$ and $r^2 > 0{\cdot}7$ as predicted.

Equation (2) was also examined using reflectances extracted from atmospherically corrected TM data. The correlation between TM-derived Chl and the Chl concentration measured in laboratory, while less ($r^2 = 0{\cdot}49$) than that for simulated TM bands, was adequate for estimation. The estimation error of Chl was less than $0{\cdot}85\,\mathrm{mgm}^{-3}$ (figure 4). This allowed maping of Chl ranging from 3 to $7\,\mathrm{mgm}^{-3}$ with four to five gradations in concentration (figure 5). The reason for the decrease in the accuracy of estimation using TM data was probably the time interval of 3 days between the ground data acquisition and the satellite overpass.

The algorithm proposed in this study was used to map Chl concentration throughout the lake and has provided a useful tool for gaining information on the spatial distribution of algae. Further investigation is required to test the consistency of the model both temporally and under a broader range of SM concentrations.

Acknowledgments

This work was supported by the Israel Water Commissioners Office and by grant no. C-372/91 from the Israel Academy of Sciences and Humanities. We wish to thank Y. J. Kaufman (NASA/GSFC) for help in calibration and analysis of the optical thickness.

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