Determination of Suspended Sediment Concentrations from CZCS Data*

Abstract

About one hundred images of the southeastern Mediterranean coastal waters, which were produced by the NIMBUS-7 CZCS, have been used to study the circulation pattern of the region. This paper is aimed (1) to adapt and calibrate an optical model for determining suspended sediment concentrations for the study area; and (2) to demonstrate the application of an interpolation technique for creating a continuous spectrum from a small number of multispectral image channels.

The study area is characterized by relatively high suspended sediments and very low chlorophyll concentrations. The optical model which was found to be suitable for estimating suspended sediment concentrations (C_{sm}) from the CZCS data has the form of $C_{sm} = 1.4 - 1.6/[Lu(550) - Lu(670)]^{1.7}/[Lu(440)/Lu(550)]$, where Lu is the upwelling radiance for the various wavelengths. This model meets the fundamental requirements of low sensitivity to both chlorophyll and atmospheric variation remaining after correction.

A method of estimating the continuous spectrum, based on a small number of multispectral image channels, along a transect crossing a front of optical density variation was developed. The spectral features of the water reflectance were analyzed. Results show that this method enables one to determine, with adequate sensitivity, the parameters of water quality of the region.

Introduction

A general problem in remote sensing of water quality is the determination of various concentrations of the materials in the water mass: (1) chlorophyll pigment existing in phytoplankton; (2) dissolved organic matter created as a result of decaying living organisms, supplied to the water body by rivers carrying humic acid from decaying vegetation and living organisms, and organic pollutants produced by human activities; and (3) inorganic sediments created by river discharge or bottom resuspension. The total reflected radiance from the water body is influenced by all these components. In order to find the distribution of suspended sediments using radiance measurements, the relation between chlorophyll and all the other constituents must be investigated because there is a connection between these parameters in various water types (Prieur and Sathyendranath, 1981; Clark *et al.*, 1980). For instance, in the open sea the total suspended material will be mainly biogenic and a little terrigenic. In coastal regions the terrigenic component (mainly silt and clays) is more dominant and changes the optical response of water to the incoming light.

The reflectance spectrum of water is created because of the differential attenuation of the sunlight penetrating into the water column, depending on the wavelength and the absorbing and scattering materials in the mixture. Typical upwelling radiance wavelength profiles for several water constituents are presented in Figure 1. For clear water (low chlorophyll and suspended sediments concentrations) the maximum intensity is located within the blue region (400 to 500 nm). An increase in the chlorophyll concentration causes a shift of the maximum peak toward the green region (500 to 600 nm). Therefore, this range is a measure of the chlorophyll concentration in the water. In both cases the intensity in the red region (600 to 700 nm) is relatively low. The spectral shape of the high suspended sediment and low chlorophyll curve is also high in the green region but also relatively high in the red region. This emphasizes the significance of the red region in the sediment concentration determination.

From these curves it may be concluded that, in order to determine one of these parameters, either chlorophyll or sediments, one should minimize the dependence on the concurrent parameters (e.g., sediments in the case of chlorophyll determination and vise versa) and maximize the sensitivity of the retrieved parameter. Another important point in the determination of concentrations from remotely sensed data is the existence of a reference waveband (channel) invariant to parameters of water quality and environmental conditions in the study area. This condition appears in the area of 510 to 520 nm, so this band is used for normalizing the radiance in the other bands (440 nm for chlorophyll and 550 nm for sediments). Finally, it should be noted that another desirable feature of the retrieval parameter is a low sensitivity to the atmospheric correction uncertainty.

Theoretical calculations performed by Tassan (1981) show that the sediment concentration can be measured with adequate sensitivity and low influence of chlorophyll by using the algorithm

$$\log[C_{sm}] = A + B \log[R(590) - R(680)] \tag{1}$$

when C_{sm} is the sediment concentration in mg/l, the coefficients A and B are linear regression constants, and $R(590)$ and $R(680)$ are reflectences in percent (downwelling to upwelling radiances in the water-air boundary) in the corresponding wavelengths.

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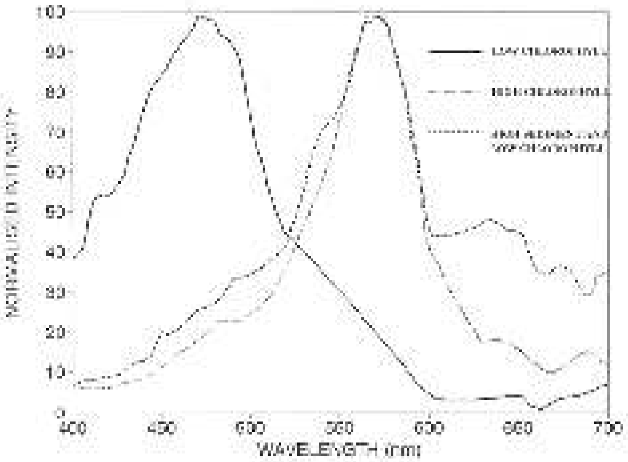


Figure 1. Reflectance spectrum from water bodies with different suspended matter content (after Walters and Schumann, 1985).

Based on experiments and data collected in the open sea and in coastal areas, Morel (1980) and Morel and Prieur (1977) proposed a model for calculating the reflectance spectrum of the water depending on the chlorophyll concentration, inorganic suspended sediment, and dissolved organic matter or yellow substance. Tassan (1981) used the proposed model in combination with an atmospheric correction algorithm (Tassan *et al.*, 1979) to estimate the sediment concentration while keeping the condition of low influence from chlorophyll pigment and low sensitivity to atmospheric disturbances. The analysis leads to the definition of the expression (Tassan and Sturm, 1986)

$$X_{sm} = \frac{[R(550) - R(670)]^a}{[R(520)/R(550)]^b} \qquad (2)$$

where X_{sm} is the sediment retrieval variable and a and b are fitting parameters from ground truth data, needed for the completion of the quantitative calibration of the model.

The above model meets the fundamental requirements of low sensitivity to both chlorophyll and atmospheric influences. They showed that the term $[R(550) - R(670)]$ is insensitive to the atmospheric correction uncertainty, unlike the $R(550)$ value which is the classical measure of suspended sediments. This results from concurrent increase of reflectance in the two channels due to atmospheric scattering but a constant difference between them. In this expression, the standard chlorophyll concentration index, $[R(520)/R(550)]$, reduces the sensitivity of the model to chlorophyll in the mixture.

Equation 2 is used to estimate the optical density of the water column affected by suspended sediment; introducing X_{sm} into Equation 1 results in Equation 3, which is used for calculating the suspended sediment concentration (C_{sm}); i.e.,

$$\log(C_{sm}) = A + B\log(X_{sm}). \qquad (3)$$

The linear regression coefficients are used for the final transformation of the algorithm to the suspended sediment concentration in mg/l. In the calibration experiment conducted by Tassan and Sturm (1986), the coefficients $A = 2.183$ and $B = 0.991$ were used and a correlation of $r = 0.83$ was found for total suspended material concentration of 2 to 15 mg/l and 0.2 to 2 µg/l of chlorophyll concentration.

The weakness of the above model is in the limited range of water constituents concentrations which can be monitored. In order to derive improved algorithms for the monitoring of different concentration ranges, and, possibly, other materials determination, more detailed spectral features are needed which can be acquired by higher spectral resolution data.

The objectives of this study are (1) to adapt and calibrate the Tassan and Sturm (1986) optical model for determining suspended sediment concentrations in coastal zone waters of the southeastern Mediterranean; and (2) to demonstrate the application of an interpolation technique for creating a continuous spectrum from a small number of multispectral image channels.

Data and Measurements

The NIMBUS-7 satellite was launched in October 1978 to orbit at an altitude of 955 km. The Coastal Zone Color Scanner (CZCS) installed on board was a multichannel scanner for measurements of the ocean color (Hovis *et al.*, 1980). The instrument was operational for 7.5 years. The system included six spectral channels, four in the visible region, each 20 nm wide in wavelengths of 440, 520, 550, 670 nm; an additional channel in the 750-nm wavelength with a 100 nm bandwidth; and a channel in the 10.5- to 12.5-µm region. The last two channels produced very noisy and insensitive output and were not used for scientific research. The 750-nm band was used only to distinguish and mask land and clouds areas.

The CZCS scanned a sector 1600 km wide with a spatial resolution of 800 by 800 m in all six channels. Every 2 minutes of scanning information was collected from an area of about 1.3 km². The data acquired were processed at the Goddard Space Flight Center (GSFC) in two main levels of processing. Level-I (Williams *et al.*, 1985a) included calibration of the data to the initial instrument parameters and level-II (Williams *et al.*, 1985b) included radiometric and atmospheric correction of the data. The corrections were intended to determine and eliminate the contribution of radiation from molecular (Rayleigh) and aerosol (Mie) scattering from the total radiance values measured in the scanner. More than one hundred Level-II images of the southeastern Mediterranean which were produced by the NIMBUS-7 CZCS have been used for this research.

An experimental cruise was undertaken off the coast of the southern part of Israel, in July 1992, along a 25-km transect perpendicular to the coastline. Laboratory results from the water sampled during this experiment demonstrate that the study area is characterized by relatively high concentrations of inorganic fine grained sediments (between 9 mg/l near the shore to about 2.5 mg/l in the open sea), very low concentrations of chlorophyll (between 0.30 µg/l near the shore to 0.028 µg/l in the open sea), and extremely low dissolved organic matter concentration.

Data Analysis

For the study area, we were primarily interested in the suspended sediment algorithm, which enhances the optical contrast between fractions with varing concentrations. For our case, we modified Equation 2 to:

$$X_{sm} = \frac{[Lu(550) - Lu(670)]^a}{[Lu(440)/Lu(550)]^b} \qquad (4)$$

where Lu is the upwelling radiance for various wavelengths.

In Equation 4, the chlorophyll term $Lu(440)/Lu(550)$ is slightly different from the one shown in Equation 2 because the chlorophyll concentration in the study area was found to be less than 1.5 µg/l as indicated in Clark *et al.* (1980). In this algorithm we apply the water leaving radiance data, the same way as Tassan and Sturm (1988) did on the image, after atmospheric corrections. The output, in radiance units, expresses the density of the optically active materials, which is measured by the radiation reflected from the total suspended materials in the upper water layer. This layer is defined by the depth at which the downwelling irradiance falls to 1/e of its value just beneath the surface.

Based on the field experiment, we were able to determine the coefficients of Equations 2 and 3; i.e.,

$$C_{sm} = 1.4 + 1.6 \frac{[Lu(550) - Lu(670)]^{1.7}}{[Lu(440)/Lu(550)]^{1}} \qquad (5)$$

This linear relationship is shown in Figure 2 with $r^2 = 0.81$. It allows the assessment of suspended sediment concentration with a standard estimation error of 0.88 mg/l.

In order to examine the water reflectance characteristics in the study area, we developed a method of estimating the continuous spectrum, based on a small number of multispectral image channels, along a transect crossing a front of optical density variation. The method is based on sampling pixels in the same spatial location of all the image channels, and interpolating between the data points using the kriging algorithm. This geostatistical technique can be used to approximate a group of randomly sampled points in a two-dimensional domain, into a two-dimensional function evenly sampled on any desired grid. In our case, the two variables were the spatial distance between sampling points along the transect and the wavelength. During the computation, we took into account the narrow bandwidth of the CZCS channels and the small amount of spectral data by giving more weighting to the variation along the spatial axis than to the wavelength axis when calculating each grid point. The estimation of the continuous spectrum was computed with about 3 nm spectral separation between 440 to 670 nm, and a spatial separation of about 800 m along the transect. This enabled us to examine various multispectral algorithms for estimating water quality properties of the area.

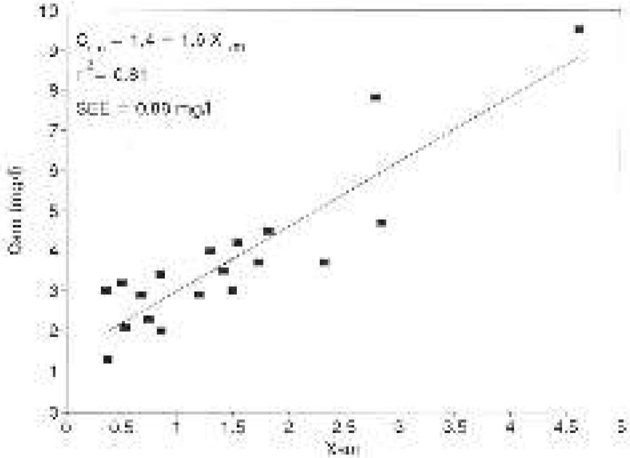


Figure 2. Suspended sediment concentration (C_{sm}) versus the reflectance function ($X_{sm} = [R(550) - R(670)]^{1.7}/[R(440)/R(550)]$).

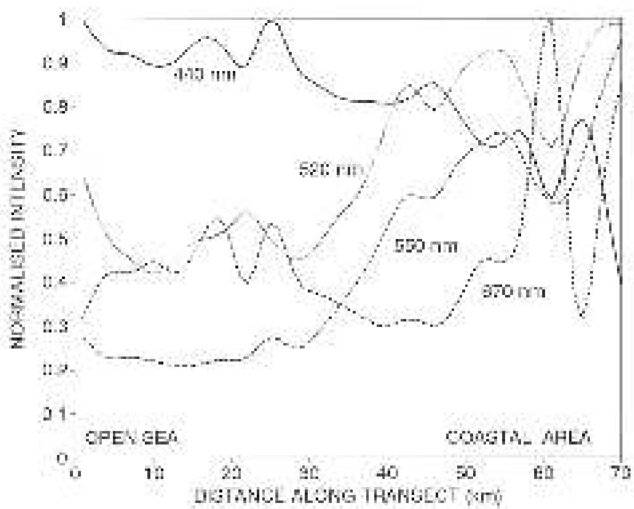
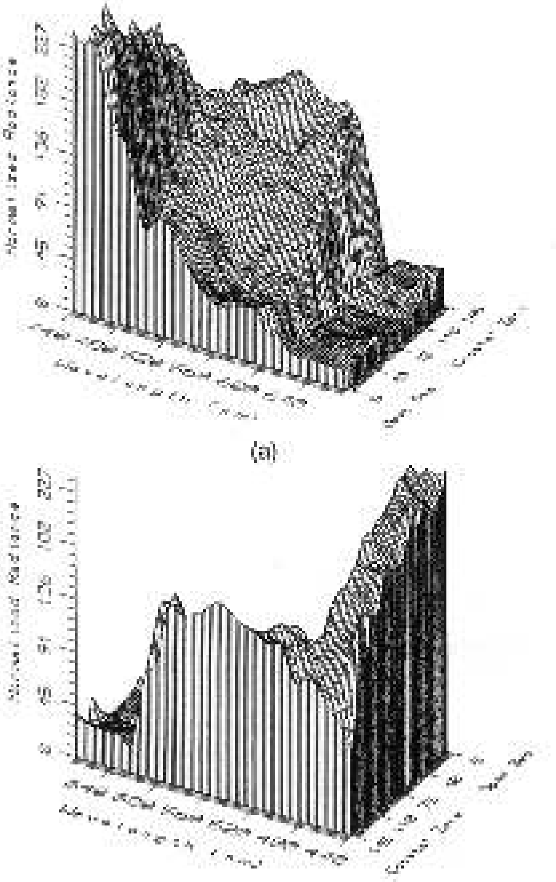


Figure 3. Normalization of the values in the CZCS channels along transect.

Results

The determination of the statistical variance in the spectral channels is a tool for measuring the information content in the channel and the sensitivity to variations of the optical properties of the water; moreover, this is a measure of the uniformity in reference channels. The result of this determination proves the quality of the aerosol correction, because the intensity in the 670-nm region is very low and shows minimum variance along the whole transect and especially in the open sea. The maximum variance appears in the 440- and 550-nm bands, so the ratio between them enables us to determine the chlorophyll content with acceptable sensitivity for most of the area. The values at 550 and 520 nm are highly correlated and show a very stable ratio of 1.3 with $r^2 = 0.94$, which indicates a low to medium range of homogeneous mixture of suspended material in the study area. This correlation reduces the number of channels in the image to three: 440, 550, and 670 nm.

Figure 3 represents normalized intensity values between 0 and 1 along a transect in every CZCS channel separately. This operation enables us to identify the gradual influence of the various components in the mixture on the reflectance spectrum. It also emphasizes the relations between various channels even though the scale of change is not the same for all of them (because every channel responds differently to varying concentrations of suspended material). The results show us the substantial increase in the 550-nm channel values towards the coastline, indicating a general increase in the suspended materials concentration. Associated with the above, also shown in Figure 3, is the decrease in the 440-nm values in the same direction due to chlorophyll absorption and the increase in the 670-nm values due to the reflectance scattering from inorganic sediments. The above relationships reflect the characteristic of the southeastern Mediterranean region, i.e., relatively high suspended sediments versus low chlorophyll concentrations. The inverse response between the 670-nm channel and all the rest of the channels indicates local anomalies in the optical density which were not corrected by the atmospheric correction procedure, for example,



(a)

(b)

Figure 4. Estimation of continuous reflectance spectrum along transect from the open sea to the coastal zone. (a) View from open sea to the land. (b) View from land to open sea. (Data from image 79026 of 26 January 1979).

cloud boundaries which did not pass the minimum threshold, causing them to be masked by the 750-nm channel. These pixels must be ignored when discussing the optical properties of the water.

In spite of the sparse spectral sampling, the continuous spectrum estimation shows acceptable profiles as compared with those in the literature for the various marine environments (Figure 4, compare with Figure 1). These results point out the efficiency of the CZCS in estimating the reflectance spectrum of the marine environment, based on a small number of wavelength bands with physical relation to the optical properties of the water quality components, in the southeastern Mediterranean.

Discussion and Conclusions

An estimation of the continuous spectrum of the water shows the typical variations expected from a change in low chlorophyll concentration and a medium range of inorganic suspended sediment concentration, along the transect from the open sea to the coastal zone. In this concentration range the radiance ratio $Lu(440)/Lu(550)$ is expected to represent, accurately, the diffuse attenuation coefficient in the reference channel ($K(520)$). This relation enables us to determine the attenuation of the radiation penetrating into the water column for the southeastern Mediterranean coastal zone, in order to evaluate water turbidity.

In the study area, we observe a conservation of color (Figure 5) which is expressed by the high correlation between the radiance ratios $Lu(440)/Lu(550)$ and $Lu(440)/Lu(670)$. The correlation is expressed by the division of the transect into two segments showing high correlation coefficients, in the open sea $r^2 = 0.87$ and in the coastal zone $r^2 = 0.98$. The high correlation in the coastal zone, resulting from a simultaneous increase in $Lu(550)$ and $Lu(670)$, enables us to distinguish, with high sensitivity, between areas in the sea where the suspended material is mainly biogenic (chlorophyll) or inorganic terrigenic. Based on this relation, we perform a semi-quantitative estimation of reflected radiance from suspended material of silt grain size based on the radiance difference $[Lu(550) - Lu(670)]$ introduced by Tassan and Sturm (1986). The expression $Lu(440)/Lu(550)$ in the denominator makes the algorithm less sensitive to chlorophyll existing in the water because an increase in this expression, caused by an increase in chlorophyll concentration, results in a decrease in the total value of the whole expression and vice versa (Figure 6). In the transect, we observe the gradual increase in the total suspended material concentration, and near the coast (4 to 8 km) we see the dominance of inorganic terrigenic component in the mixture.

The image data enable us to determine the multispectral algorithm for estimation of bio-optical properties of the southeastern Mediterranean, from the link between the reflectance and the chlorophyll content in the water. We can say that the algorithm proposed by Clark *et al.* (1980) is effective for the determination of chlorophyll concentrations in the southeastern Mediterranean coastal zone. The ratio $Lu(440)/Lu(550)$ is good for an estimation of chlorophyll concentration of up to 1.5 μg/l in areas where the majority of the material is biogenic. In the open sea, we have to switch to the ratio $Lu(520)/Lu(550)$ while keeping spatial continuity in the image (Figure 6). This algorithm is effective for mapping low to medium range concentrations of chlorophyll in our region. This mapping is an important tool in fisheries planning and, in small scale, is an indirect indicator of various pollutants influencing the phytoplankton population along the coasts of Israel (for example, industrial toxic wastes

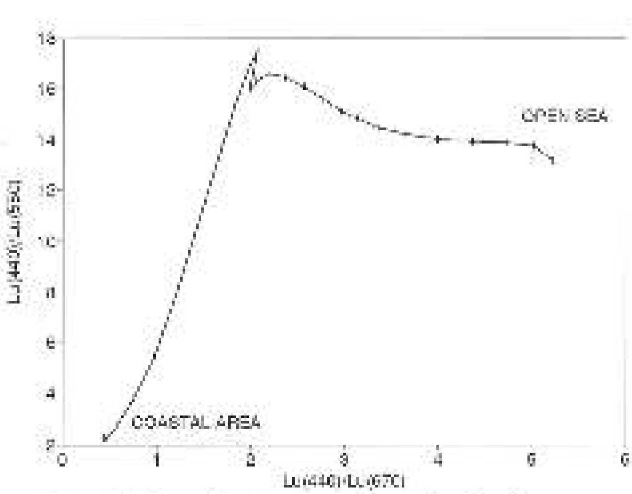


Figure 5. Correlation between the ratios of radiances.

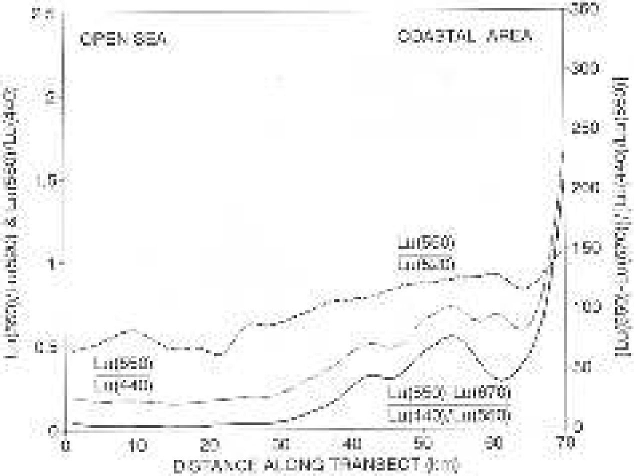


Figure 6. Water quality algorithms evaluation along transect.

which deplete the population or highly nutrient garbage dumps which allow the population to bloom).

By using the interpolated spectrum technique, one can approximate the spectral characteristics of the water wavelengths, other than the bands of the CZCS scanner. For example, one can test the theoretical algorithm presented in Equation 1, which is based on wavelengths that are not among the CZSC channels.

The CZCS data and the improved algorithm, developed to interpret these data, were found suitable for the study area and the concentration ranges found in it. They enable us to determine, with adequate accuracy, the parameters of water quality of the southeastern Mediterranean and the coastal zone of Israel. Even though the scanner is no longer operative, the experience accumulated in this study is a basis for future studies with future spectrally compatible systems using the same algorithms.

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