

# Water Color in Eastern Canadian Inshore Areas

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## Abstract

Water color measurements from satellites have been related to chlorophyll concentration for oceanic water masses. In inshore areas, the concentration of suspended sediment present in the water dominates the color of the upwelling light spectrum. Only when suspended solid concentrations were less than 1 mg/l could the long wavelength fluorescence of chlorophyll *a* be determined in the *in situ* light spectrum. Inshore waters tended to have a high absorption of short wavelength light, thus complicating the blue-green color variations produced by chlorophyll *a* in oceanic waters. In general, the spectral irradiance of inshore waters could not be explained by the color algorithms derived for oceanic waters.

## Introduction

The possibility of obtaining extensive coverage of the oceans by satellite surveillance is of potential interest to marine oriented science and industry. Both ocean color and sea surface temperature are presently being monitored by satellite systems and represent parameters of interest to fisheries biologists. Ocean color is recorded by the Coastal Zone Color Scanner (CZCS) carried on board the Nimbus-7 satellite launched in October 1978. The scanner records upwelling light from the ocean in five spectral bands, and considerable scientific attention has been given to developing algorithms relating sensor signals to parameters such as chlorophyll and suspended solids.

Water color ratios have been used in attempts to quantify surface chlorophyll in ocean waters (Clark *et al.*, 1980; Smith and Baker, 1978). Various blue-green ratios have been suggested to explain chlorophyll concentrations, and the disagreements between various algorithms have been highlighted by Højerslev (1981). The greatest disagreement occurs for coastal waters where concentrations of dissolved organic material can mask the chlorophyll signal, where river outflows can produce high suspended sediment levels, and where tidal mixing can induce resuspension of bottom material. The diversity of factors influencing water color in these cases requires sea color algorithms that are specific for the particular water masses (Højerslev, 1981).

Coastal water masses requiring special consideration in algorithm development must first be identified in terms of their optical properties. Jerlov (1968) was the first to identify the characteristics of coastal waters,

*viz.* (a) high attenuation of ultra-violet and blue wavelengths, (b) decreased penetration of visible light at all wavelengths relative to oceanic waters, and (c) a shift in the maximum spectral transmission towards longer (red) wavelengths. Jerlov (1978) defined three oceanic water types (I, II, III) and five coastal water types (1, 3, 5, 7, 9) according to their optical characteristics alone. The relationships between normalized irradiance transmittance per 10 meters and wavelength for oceanic water types I and III and coastal water types 1 and 9 are shown in Fig. 1. A normalized plot was used to emphasize the spectral rather than magnitude differences between the water masses. The maximum transmission value per 10 m for coastal type 9 is only 1/278 of the value of the maximum for oceanic type I. At the short wavelengths (400–450 nm), irradiance transmission for the first coastal type (1) is much less than that for the last oceanic type (III). This loss of blue light for coastal water types traditionally has been associated with the occurrence in coastal water of a complex mixture of organic compounds known under the collective name of yellow substance (Kalle, 1966). The positions of four of the CZCS wavebands are indicated in Fig. 1. Coastal water types would exhibit only low transmission properties at 443 nm (CZCS band 1), and all defined water types would transmit minimal light information at 670 nm (CZCS band 4). The optical characteristics of coastal waters at various locations in the Bay of Fundy and around Nova Scotia are examined in this paper.

## Materials and Methods

Upwelling spectral irradiance measurements were taken at 1 m depth with a Techtron quantaspectrometer

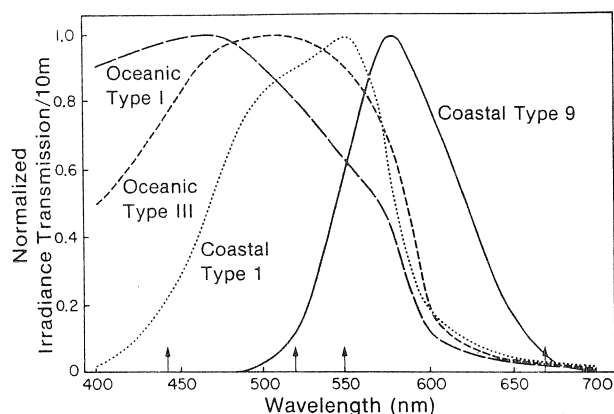


Fig. 1. Normalized irradiance transmission per 10 m versus wavelength for Jerlov's (1978) water classification types. (Arrows represent CZCS wavebands.)

TABLE 1. Locations of irradiance measurements and water samples in eastern Canadian coastal waters with ranges of suspended sediment concentrations.

Sampling locations	Range of suspended solids (mg/l)
Bay of Fundy: Minas Basin (N. S.)	4-150
Off Digby (N. S.)	0.6-1.6
Off Saint John (N. B.)	0.5-3.7
Off Yarmouth (N. S.)	0.4-2.6
St. Margaret's Bay (N. S.)	0.4-3.6
Bedford and Halifax Harbor (N. S.)	0.4-4.9
St. George's Bay (N. S.)	0.6-4.5

at inshore locations listed in Table 1. These subsurface measurements were made under a variety of atmospheric light conditions without the benefit of simultaneous above-surface measurements. The magnitude of the spectral signals were not therefore readily comparable, and each spectral profile was normalized to its maximum signal level. This approach retained all spectral information and still allowed ratios to be calculated.

For each spectrum, a water sample was taken at 1 m depth and analyzed for the following parameters: suspended solids, chlorophyll, phaeophytin, dissolved organic carbon, particulate organic carbon, and salinity. Standard methods for sampling and analysis of these parameters were used in all cases, i.e. for chlorophyll, extraction in acetone and determination by fluorescence, and for nutrients, the analysis followed standard methods on a nutrient autoanalyzer. Suspended solid estimates represent dry weight per volume of all material retained by a 0.4 micron nucleopore filter, irrespective of the composition of the suspended material, and hence the ranges of suspended solid concentrations for the different samples may

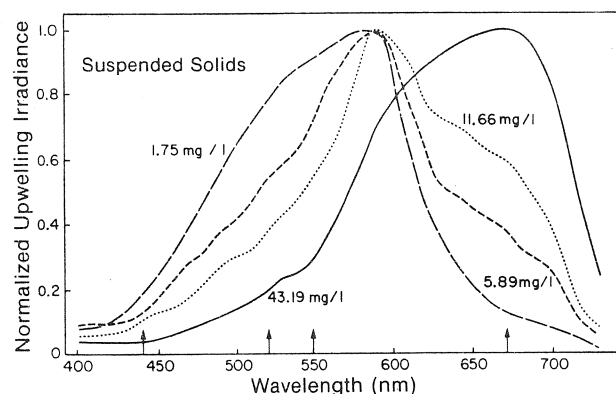


Fig. 2. Normalized upwelling quantum irradiance at 1 m depth versus wavelength for various concentrations of suspended solids in coastal waters of eastern Canada. (Arrows represent CZCS wavebands.)

relate to different types of material. Additional depth samples were also taken in clear water with low concentrations of suspended solids in order to detect possible stratification effects on sample values.

## Results

### Coastal spectra and sediment load

Normalized upwelling quantum irradiance spectra (1 m depth) for four different concentrations of suspended solids from 1.7 mg/l to 43.2 mg/l are shown in Fig. 2, in relation to the four CZCS wavebands. The relative signal level at 670 nm (CZCS band 4) increases directly with increasing concentration of suspended solids. Bukata *et al.* (1980) showed, for concentrations of suspended solids less than 10 mg/l, that the magnitude of reflected irradiance at 670 nm is directly related to the concentration. For concentrations in the range of about 1-12 mg/l (Fig. 2), the wavelength of the spectral maxima changed by less than 10 nm around 590 nm, but signal levels decreased at wavelengths between 450 and 550 nm and increased at wavelengths between 600 and 700 nm. For larger concentrations of suspended solids, the spectral maximum shifts towards longer (red) wavelengths. The signal levels at 443 nm (CZCS band 1) were small and often masked by the instrumentation noise level.

The upwelling quantum irradiance spectra for coastal waters was found to be dominated by the suspended solid load for concentrations in excess of 5 mg/l but still highly influenced for concentrations in the range of 1-5 mg/l. In these cases, sediment load has a primary effect on the spectra, and all other substances (chlorophyll, dissolved organics, etc.) have a secondary or masked role.

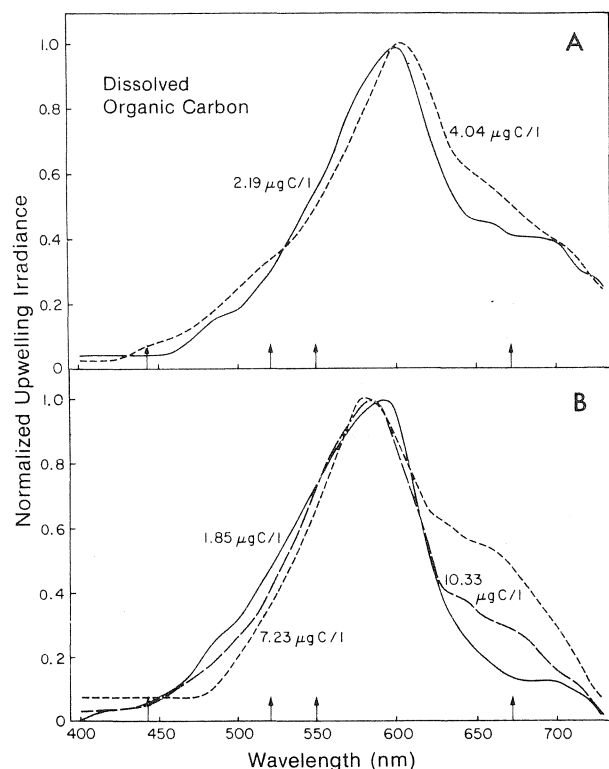


Fig. 3. Normalized upwelling quantum irradiance at 1 m depth versus wavelength in coastal waters of eastern Canada, for (A) different dissolved organic carbon concentrations and suspended solids, and (B) different dissolved organic carbon concentrations with approximately similar content of suspended solids. (Arrows represent CZCS wavebands.)

### Coastal spectra and dissolved organic carbon

Coastal waters are often typified by the presence of yellow substance (Jerlov, 1978; Hojerslev, 1981) which can itself be approximated on a local scale by the level of freshwater input (salinity) or dissolved organic carbon. However, coastal waters also contain variable quantities of other material, such as organic sediments, inorganic sediments, chlorophyll and phaeophytin. Identifying the influence in just one of these substances can therefore be difficult. Normalized upwelling spectra for concentrations of suspended solids of 1.26 and 7.92 mg/l containing dissolved organic carbon concentration of 4.04 and 2.19 µgC/l respectively, are shown in Fig. 3A. In this case, a water mass with high dissolved organic carbon content and low suspended solid concentration produced approximately the same spectral profile, and hence similar spectral ratios, as a water mass with lower dissolved organic carbon content and higher load of suspended solids. The effect of dissolved organic carbon content on the short wavelength portion of the spectrum of upwelling irradiance is variable and may not even be observed at higher levels of suspended solid concentrations. Normalized

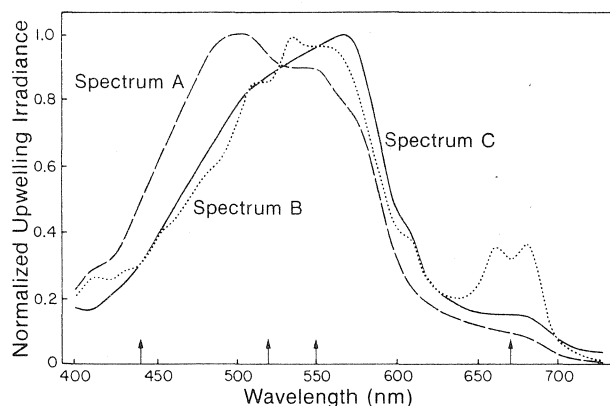


Fig. 4. Normalized upwelling quantum irradiance at 1 m depth versus wavelength for suspended solid concentrations less than 1 mg/l in coastal waters of eastern Canada. (Arrows represent CZCS wavebands.)

TABLE 2. Concentration levels of chlorophyll, phaeophytin and suspended solids for the spectra shown in Fig. 4.

Spectrum (Fig. 4)	Chlorophyll (µg/l)	Phaeophytin (µg/l)	Solids (mg/l)
A	0.68	0.47	0.72
B	5.99	0.56	0.58
C	1.19	0.41	0.50

quantum irradiance spectra for sediment loads of 3.50, 3.59 and 3.37 mg/l, with dissolved organic carbon concentrations of 10.33, 7.23 and 1.85 µgC/l respectively (Fig. 3B), do not exhibit any additional decrease at short wavelengths over that already produced by the sediment load. The spectra at 670 nm show variations consistent with but larger than increasing sediment loads, indicating the possible influence of another substance.

The spectra shown in Fig. 3 exhibit features that are consistent with sediment-laden waters, i.e. larger signals at 670 nm than at 443 nm and spectral maxima at wavelengths greater than 550 nm.

### Coastal spectra and chlorophyll

The upwelling irradiance spectrum in coastal waters appears to be dominated by the suspended load. In order to examine any relationship between chlorophyll and water color for coastal areas, only spectra for suspended solid concentrations less than 1 mg/l were selected. Figure 4 shows three such spectra with the associated levels of concentration given in Table 2. Spectrum B, which was obtained off Yarmouth, Nova Scotia, in early June in a known biologically productive area, exhibits a small secondary mode around 670 nm which can be identified with the known fluorescent peak of chlorophyll *a*. Spectra A and C

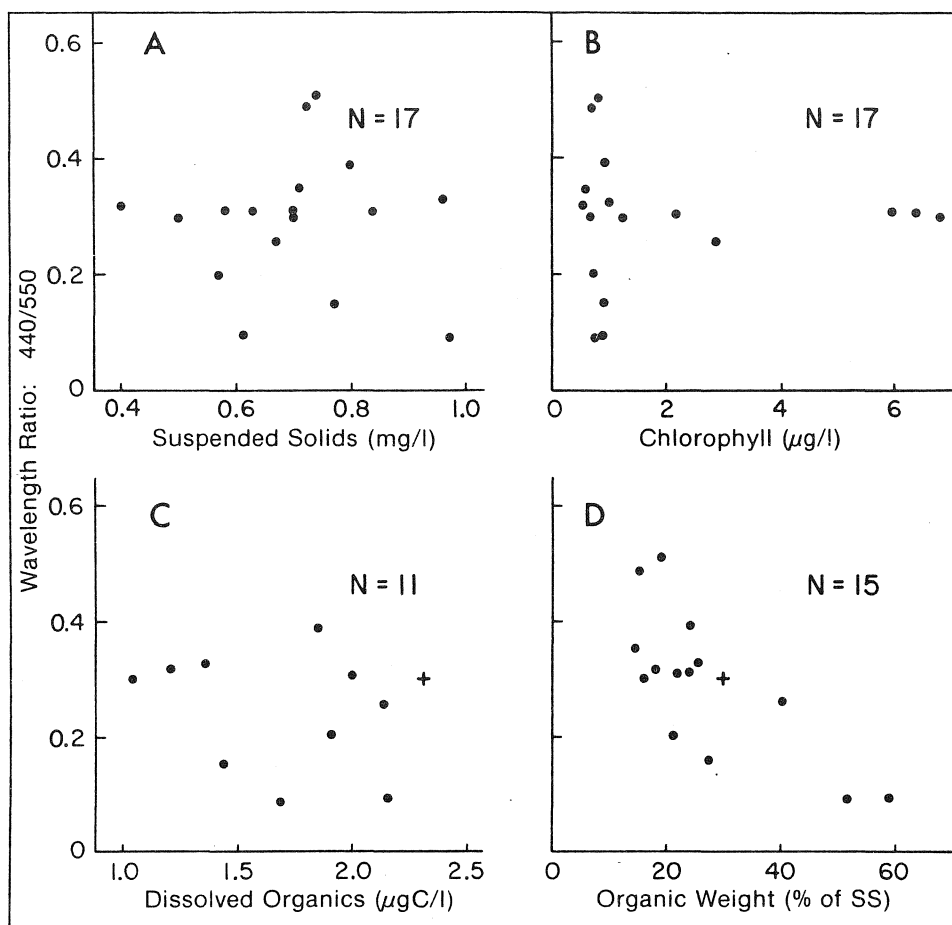


Fig. 5. Quantum irradiance color ratio (440/550 nm) for profiles with less than 1 mg/l suspended solids versus (A) suspended solids; (B) chlorophyll; (C) dissolved organic carbon; and (D) percentage organic weight of suspended solids. (+ denotes station average for concentration value.)

were taken in water masses with much lower concentration of chlorophyll but with similar levels of phaeophytin and suspended solids. These low chlorophyll spectra are not very different from the high chlorophyll profile except for the fluorescent peak at the long wavelengths. All three spectra exhibit features that are consistent with the oceanic spectra observed by Clark *et al.* (1980), with low signal levels at 670 nm (except for fluorescent effects), small variation at 520 and 550 nm, and clear (above noise level) signals at 443 nm. The spectra obtained for suspended solid concentrations below 1 mg/l therefore most nearly approach oceanic measurements.

For data from all locations with less than 1 mg/l concentration of suspended solids, no consistent relationships were evident in plots of blue-green quantum irradiance ratios (450/550 nm) against concentrations of suspended solids, chlorophyll and dissolved organics (Fig. 5A, B, C). In fact, no relationship could be detected with any absolute level of concentration (suspended inorganics, phaeophytin, etc.). However, a

similar plot for percentage (by weight) of organic material in the suspended load (Fig. 5D) does indicate a trend of decreasing color ratio with increasing organic composition, at least for water masses containing very low concentrations of suspended solids.

### Discussion and Conclusions

Calibration of the CZCS with *in situ* data for some geographic areas has given rise to algorithms relating ocean color ratios to chlorophyll concentrations (Morel and Gordon, 1980). Successful use of any of these algorithms for non-calibrated areas depends on the similarity of optical features of the calibrated and non-calibrated areas. It has been shown in this study that waters of the Bay of Fundy, St. George's Bay, St. Margaret's Bay and Halifax Harbour did not have optical properties of oceanic water masses, and available CZCS algorithms could not therefore be used for these coastal areas. It is important to note that not only would the algorithms change for these coastal areas but also

the dependent variable would probably change from chlorophyll to suspended solids.

The coastal upwelling spectra presented in this paper have optical features different from those associated with oceanic spectra. In particular, the coastal spectra exhibit non-zero contributions at 670 nm which appear to be related to suspended solid concentrations. As the suspended load increases, the short blue-green wavelengths are attenuated further but the long wavelengths are affected by additional light from scattering processes. At sufficiently high sediment concentrations, the CZCS band 4 (670 nm) would register the maximum spectral water signal.

The occurrence of yellow substance in coastal waters causes strong absorption of ultra-violet light with some accompanying attenuation of blue (short wavelength) light. Both salinity and dissolved organic carbon concentrations can be indicators of ultra-violet absorption in localized situations but are non-conservative in general cases. Although optical measurements in this study were made at several localities over a broad coastal area, neither dissolved organic carbon nor salinity measurements provided a consistent explanation of short wavelength attenuation of coastal spectra. Hence, a CZCS satellite image covering such coastal areas would be unable, with present knowledge, to give consistent indication of concentrations of such substances.

Coastal upwelling spectra for low suspended solid concentrations (less than 1 mg/l) exhibited oceanic features for wavelengths greater than 520 nm. However, for wavelengths less than 520 nm, the coastal spectra remain depressed below levels expected for corresponding chlorophyll concentrations in oceanic waters. The color ratio for one station with high chlorophyll concentration was not inconsistent with ratio

predictions from oceanic models. Data for all of the low chlorophyll stations gave blue-green ratios much lower than oceanic model predictions. Inclusion of data from clear (low concentration) coastal water masses in algorithm calibrations would result in disagreement with oceanic models, and, in cases of limited sampling, inverse or negative relationships could even be deduced.

Little or no optical information on water type is available for other eastern Canadian waters (e.g. Scotian Shelf, Labrador Sea, etc.) for comparison with optical features of water masses in CZCS calibrated areas. CZCS data for these waters could be used for chlorophyll mapping if *in situ* data were available or if the optical characteristics of the water masses were established.

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