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In Situ Colour Measurements on the Great Lakes

K.P.B. Thomson and J. Jerome

SCIENTIFIC SERIES NO. 51

(Résumé en français)

INLAND WATERS DIRECTORATE,
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Contents

Tables

Illustrations

Abstract

Measurements of upwelling and downwelling spectral irradiance have been used to compute *in situ* colour for Lakes Ontario and Superior. The computations of the colour are based on the CIE chromaticity system. Tristimulus values for a network of stations and a number of different time periods are analysed with reference to limnological parameters. The analysis shows that suspended inorganic material and biological activity affect the *in situ* colour in characteristic ways. In effect, three principal water regimes can be identified by their characteristic or dominant wavelength. These are clear water with little dissolved or suspended substances, water that is biologically productive, and water with heavy sediment loading.

The *in situ* colour also indicates basic differences between the two lakes that are related to their productivity.

Résumé

On s'est servi des résultats des mesures du spectre de rayonnement associé aux mouvements ascendants et descendants des eaux pour calculer la couleur naturelle des lacs Ontario et Supérieur. Ces calculs ont été fondés sur le système à chromaticité de la Commission internationale de l'éclairage (C.I.E.). On a analysé les coefficients trichromatiques obtenus par un réseau de postes et pour différentes périodes de temps, en rapport avec des paramètres limnologiques. L'analyse démontre que les matières inorganiques en suspension et l'activité biologique exercent une action caractéristique sur la couleur naturelle de l'eau. n effet, on peut identifier trois types principaux d'eaux. Ce sont les eaux claires contenant peu de matières en suspension ou en dissolution, les eaux biologiquement productives et les eaux à fortes teneurs en sédiments.

La couleur naturelle dénote aussi entre les deux lacs des différences fondamentales reliées à leur productivité.

In Situ Colour Measurements on the Great Lakes

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INTRODUCTION

The colour of lake water, whether observed remotely or *in situ*, is a subject of limnological interest. The phenomena that affect the *in situ* colour of ocean or lake water include sediment loading, productivity, algae species, and man-made effluents.

The basic trends on how the colour changes according to the turbidity of the water are well known, with a shift from blue through green to red as the water becomes more turbid. Direct observation and assessment of the *in situ* colour of ocean water using optical techniques has been carried out by a number of workers (Jerlov, 1968; Duntley, 1963). Similar techniques have been applied to lakes (Smith, Tyler and Goldman, 1973), and in some instances limnologists have used optically determined colour as a means of lake classification (Sauberer, 1962).

A knowledge of the spectral distribution of the upwelling and downwelling irradiance of natural light in water provides a means of objective colour analysis for a particular water body. If the irradiance data is subjected to a colour analysis based on a recognized chromaticity system, then colour parameters that are repeatable and comparable, from lake to lake, can be established. Essentially, a colour classification of this nature replaces the plot of irradiance as a function of wavelength by a set of coordinates, which make comparison of lake to lake or station to station more convenient. The technique applied to obtain objective colour data for the Great Lakes is based on the CIE chromaticity system (Committee on Colorimetry, 1953). In this system a set of parameters, called tristimulus values, can be calculated from up- and downwelling spectral irradiance data. These parameters, plotted on a CIE chromaticity chart, numerically define the colour of a particular irradiance measurement in terms of a dominant wavelength (λ_D) and its purity or monochromaticity (Jerlov, 1968).

A tristimulus colour system implies that the dominant wavelength is composed of a combination of three colours. In the CIE system, the basic definitions of the tristimulus values are as follows:

$$X = \int E_\lambda \, \overline{x}_\lambda \, d\lambda$$
$$Y = \int E_\lambda \, \overline{y}_\lambda \, d\lambda$$
$$Z = \int E_\lambda \, \overline{z}_\lambda \, d\lambda$$

Where E_λ is the function that describes the spectral properties of the light source (in this case the up- or downwelling *in situ* light field), $\overline{x}_\lambda$, $\overline{y}_\lambda$ and $\overline{z}_\lambda$ are CIE standard colour mixture parameters. These parameters ($\overline{x}_\lambda$, $\overline{y}_\lambda$, $\overline{z}_\lambda$) are based on standard luminosity responses of the human eye (Judd, 1933). The colour data are plotted on the chromaticity diagram in the form of normalized coordinates x, y, z, which are defined as follows:

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z}$$

With this normalization the sum of the coordinates x, y and z is unity, and hence only two coordinates, usually x and y, are required to uniquely define the dominant wavelength. For complete colour analysis two other factors must be considered. These are a source of illumination to which the colours can be referenced, and a medium which changes or modifies the spectral distribution of the illuminating source. Following the criteria established by Smith, Tyler and Goldman (1973), we have applied the CIE standard source C as the achromatic or white point for the chromaticity coordinates. This source C is a good approximation to average daylight. The medium which changes the spectral distribution by absorption and scattering of the incident light field is the lake water. Figure 1 shows an example of the CIE chromaticity diagram, with the tristimulus values of the upwelling and downwelling irradiance plotted for a number of Lake Ontario stations.

For an observer above the lake, who views both the reflected and upwelling components of the light field, the colour assessed by him will be, to a good approximation, defined by the dominant wavelength of the upwelling irradiance close to the surface.

Upwelling and downwelling spectral irradiance data for Lakes Ontario and Superior were used to compute the tristimulus values at several depths for a number of representative stations. The spectral irradiance data for both lakes were measured using a quanta spectrometer (made by A & B Incentives, Sweden).

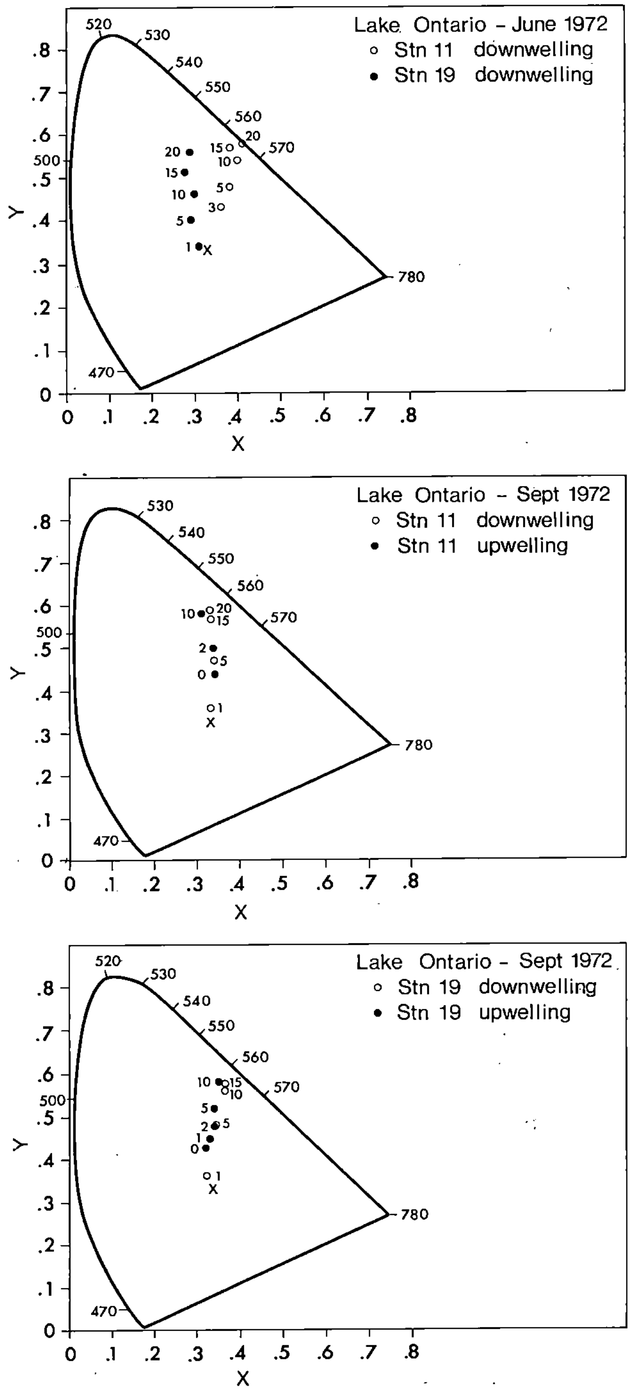

Figure 1. Chromaticity diagrams for Lake Ontario stations 11 and 19. Tristimulus values are shown by dots and circles and the standard source (Committee on Colorimetry, 1953) is denoted by X. Numbers beside each point indicate the depth in metres. The position of spectrally pure wavelengths from 470-780 nm are indicated on the edge of the chromaticity diagram. The intersection on the wavelength axis of a line drawn from the source "X" through a plotted point defines the dominant wavelength λ_D. The distance from the source to the point divided by the distance from the source to the intersection on the wavelength axis determines the purity.

DISCUSSION OF RESULTS

Lake Ontario

The Lake Ontario data were obtained during a series of optical measurements carried out in 1972 over a period of several months (Thomson and Jerome, 1974). Spectral irradiance data were obtained at two stations, one (station 19) representing the midlake region and the other (station 11), the near-shore region (see Fig. 2).

Figure 1 shows an example of the tristimulus values obtained for the two stations for the month of September; both downwelling and upwelling values at a number of depths are shown. The interesting points to note are:

(1) the similarity between the two stations;
(2) no significant change of colour with depth for both the upwelling and downwelling values.

The colour derived from the September values of the near-surface upwelling irradiance is in the region of 550-560 nm (see Tables 1 and 2). For other months, the colour coordinates change (see Tables 1 and 2) with the behaviour in the surface values, ranging from 500-530 nm (blue-green) in spring and fall to 550-560 nm (green) in the summer. It is evident that the colour of the water must be related to the biomass cycle, and indeed, the general variations of the colour data follow this cycle very closely (see Fig. 3). At station 19 the colour range 550-560 nm for the near-surface upwelling irradiance is not evident even in July, whereas at station 11 this range of values is attained in June (see Fig. 1). This difference between the two stations corresponds to the peaks in the biomass cycle in the midlake and near-shore regions (Stadelmann, Moore and Pickett, 1974).

The "purity" of the dominant wavelength (see Fig. 1) as indicated in Tables 1, 2, etc., shows clearly how water acts as a monochromator. A high percentage of purity implies a more compressed or monochromatic light source. As one would expect, the purity typically increases with depth.

The greatest change in the *in situ* colour occurs over the period September to October. During this same time period, parameters such as chlorophyll, total particulate carbon, etc., are steadily decreasing (see Fig. 3). A similar but inverse cycle is also apparent between the early spring and the June and July peak biomass periods. It is therefore apparent that the changes in colour are related strongly, but not exclusively, to the productivity cycle.

Lake Superior

A summary of the chromaticity data for three cruises in May, July and September, is shown in Tables 3, 4 and 5.

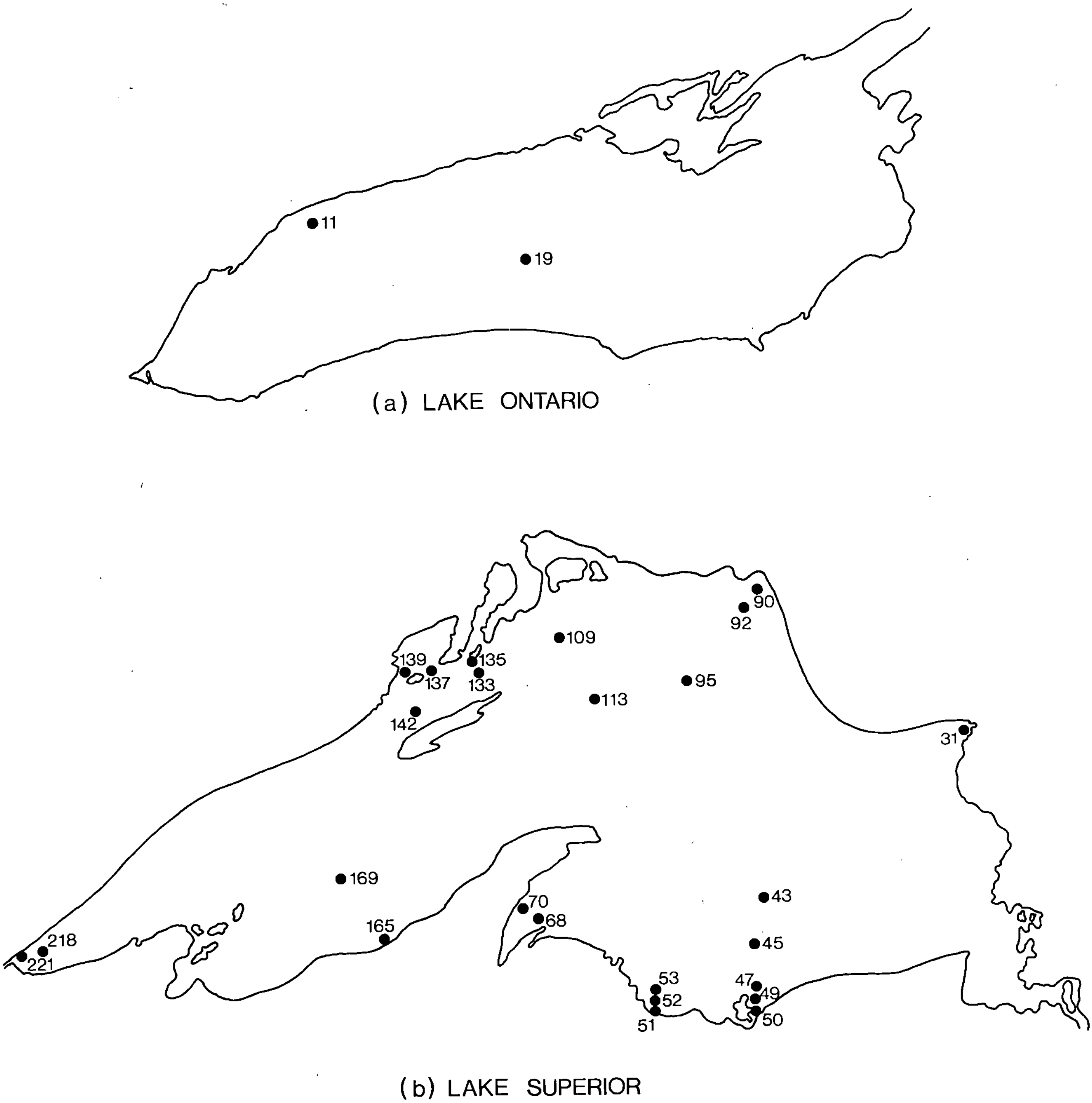

Figure 2. Station locations on Lakes Ontario and Superior.

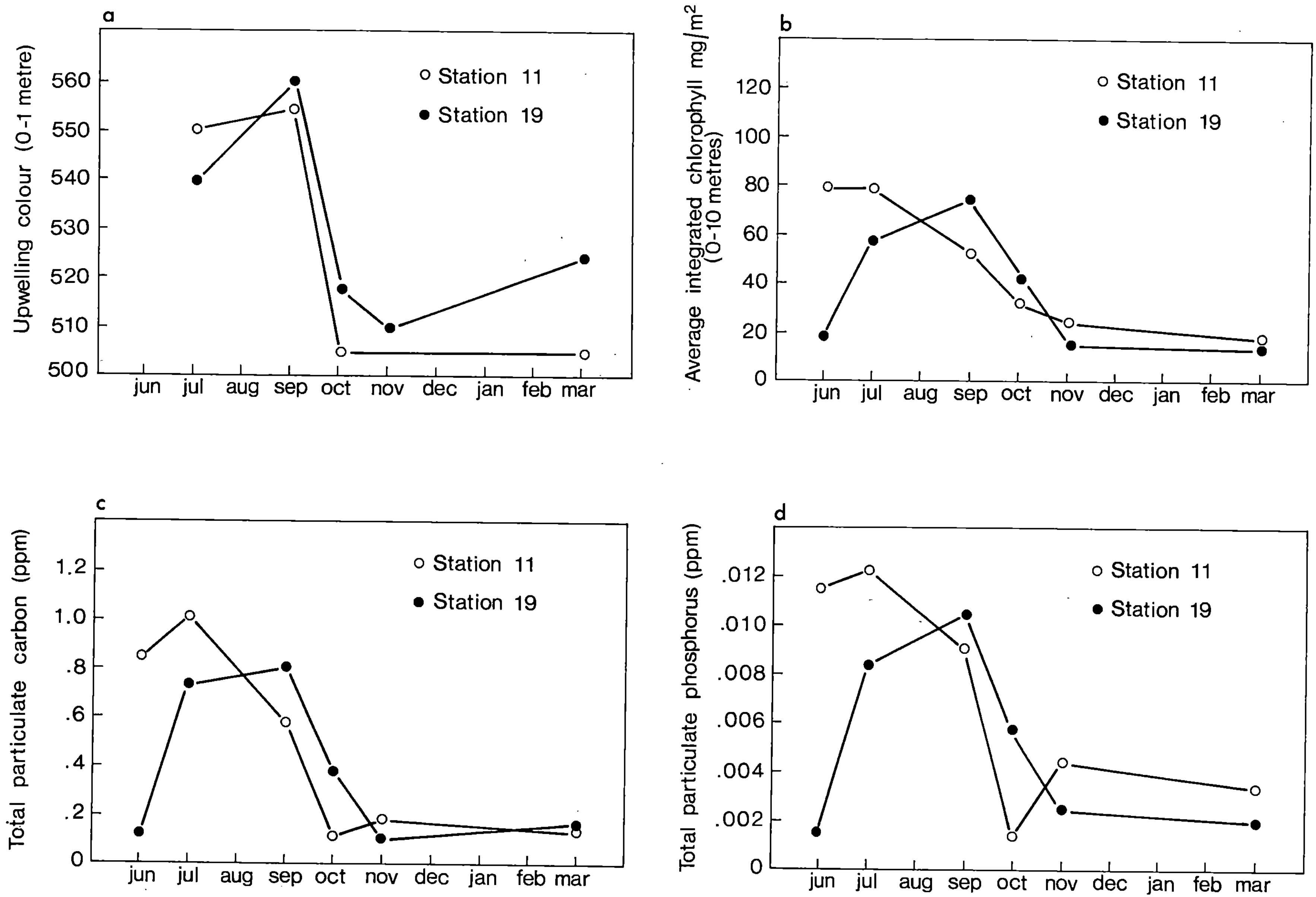

Figure 3. Upwelling colour and limnological data for Lake Ontario stations 11 and 19.

During the May cruise both upwelling and downwelling data were obtained (see Table 3) for a number of stations. Deep water stations (i.e., 142 and 169; see Fig. 2) show surface colour values close to 500 nm. Even the downwelling data show a dominant wavelength in the region 515 nm at a depth of 20 metres for these two stations. Transmittance values measured at a depth of 1 metre at these deep water stations are typically 60-70% (see Table 3) referred to a clear air path.

Table 1. Lake Ontario optical data, station 19, 1972

	Depth (m)	λ_D (nm)	% Purity	
June	1	498	7	Downwelling
	5	515	14	
Solar elevation	10	540	30	
56°	15	538	57	
	20	550	60	
July	1	498	5	Downwelling
	5	554	28	
Solar elevation	10	555	70	
64°	15	560	82	
	20	555	80	
	0	535	21	Upwelling
	1	550	30	
	5	555	62	
September	1	520	5	Downwelling
	5	555	45	
Solar elevation	10	558	75	
47°	15	558	75	
	1	550	28	Upwelling
	5	558	56	
	10	552	76	
October	1	502	4	Downwelling
	5	515	16	
Solar elevation	10	540	30	
30°	15	515	30	
	20	545	60	
	0	515	7	Upwelling
	1	522	18	
	2	540	28	
	5	555	63	
November	1	494	10	Downwelling
	5	515	15	
Solar elevation	7	520	20	
25°				
	1	510	23	Upwelling
	5	522	28	
March	1	502	6	Downwelling
	5	530	23	
Solar elevation	10	515	60	
23°				
	1	525	19	Upwelling
	5	530	33	

Stations 221 and 218 in the western basin indicate more of a green-blue colour, with λ_D in the order of 540 nm. The percent transmittance at these two stations is low: 20-40%.

The longest colour wavelengths were observed at station 165 and at other stations in the same area (see Fig. 2). Observations made over the year show that this south coastal area is one of generally high turbidity, with the mean circulation carrying the suspended sediment along this coast. Transmittance values at 1 metre in the area of station 165 were in the order of a few percent during the May cruise (see Table 3). The high values of λ_D, 570-600 nm, measured at stations in this area must be related principally to suspended sediments. With reference to the Lake Ontario data, high chlorophyll content is

Table 2. Lake Ontario optical data, station 11, 1972

	Depth (m)	λ_D (nm)	% Purity	
June	3	562	36	Downwelling
	5	565	59	
Solar elevation	10	565	82	
26°	15	560	83	
	20	562	90	
July	1	569	24	Downwelling
	5	560	45	
Solar elevation	10	560	66	
65°	15	555	70	
	20	560	85	
	0	545	23	Upwelling
	1	560	42	
	5	565	86	
September	1	555	10	Downwelling
	5	557	45	
Solar elevation	15	555	72	
15°	20	554	82	
	0	555	36	Upwelling
	2	555	56	
	10	550	69	
October	0	505	24	Upwelling
	1	502	24	
Solar elevation	2	510	29	
9°				
March	5	498	14	Downwelling
	10	515	32	
Solar elevation	15	530	53	
35°	20	540	65	
	1	505	24	Upwelling
	5	530	32	

associated with colour wavelengths in the range 550-560 nm. This is also consistent with our observations of the behaviour of the spectral transmittance curves for the Great Lakes (Thomson and Jerome, 1974). Thus, dominant colour wavelengths in the range 570-600 nm are more likely to be indications of sediment loading than peaks in biomass activity.

The July data (Table 4) show that, in general, the dominant wavelength tends to be the shorter (blue) wavelengths. Only a few stations (142, 139, 90, 31) indicate colour wavelengths greater than about 525 nm. Of these stations only two are in areas where turbid conditions are generally observed, i.e., 139 in Thunder Bay and 31 in the inshore area of Michipicoten Bay.

During the September cruise only downwelling irradiance was available (see Table 5). However, because of the similar behaviour of the two components of the spectral irradiance, the general trends can be recognized from the downwelling data. The stations far from coastal influence (43, 68, 113 and 169) have colour wavelengths in the range 530-550 nm. The transmittance at these stations covers the range 55-65%. Stations close to shore—165, 218 and 221—show wavelengths in the range 550-565 nm.

The most important observation to be made about the Lake Superior data is the general absence of colour wavelengths between 550 and 560 nm. Judging from the behaviour of the colour in Lake Ontario, this must reflect the low productivity in Lake Superior as a whole. It is significant that a simple but objective colour analysis of this nature pinpoints clearly a basic limnological difference between the two lakes.

CONCLUSIONS

The *in situ* colour data for Lake Ontario and Lake Superior indicate clearly variations in the biomass cycle and sediment loading. In general, three water regimes can be identified by the colour or dominant wavelength of the near-surface upwelling irradiance. These are

(1) clear water with little dissolved and/or suspended substances; $\lambda_D \sim 490\text{-}530$ nm,
(2) water that is biologically productive; $\lambda_D \sim 550\text{-}560$ nm,
(3) water with heavy sediment loading; $\lambda_D > 565$ nm.

In case (2) it is apparent from the Lake Ontario and Lake

Table 3. Lake Superior optical data, May 1973

Station	Depth (m)	λ_D (nm)	% Purity	Chlorophyll* μg/1	% Transmittance at 1 metre	
221	1	540	13	1.8	20	Downwelling
	7	540	20			$\Theta = 16°$
	1	540	20			Upwelling
218	1	540	6	1.5	42	Downwelling
	5	540	25			$\Theta = 35°$
	1	540	25			Upwelling
169	5	505	25	0.9	69	Downwelling
	15	510	32			$\Theta = 32°$
	20	515	38			
	1	500	24			Upwelling
	5	505	26			
142	3	500	10	0.9	71	Downwelling
	5	505	19			$\Theta = 27°$
	15	510	32			
	20	515	37			
	1	498	57			Upwelling
165	2	580	74	1.8	<1	Downwelling
	6	595	100			$\Theta = 64°$
	3	585	100			Upwelling

*Chlorophyll data is for a 0-20 m integrated sample.
Θ is solar elevation.

Superior data that the dominant colour in the surface layers does not attain the wavelength range 550-560 nm until the chlorophyll values are in the order of 40 mg/m^2 (0-20 metres).

On a yearly basis, chlorophyll values on Lake Ontario cover the range 20-150 mg/m^2 (0-20 m), whereas in Lake Superior the range is, in general, 5-50 mg/m^2 (Nicholson, unpublished data). Hence, the colour changes in Lake Superior are associated more with suspended inorganic sediment, and the biological activity does not play a major role. For Lake Ontario, especially for the midlake stations, it is clear that the seasonal colour changes are more closely related to the biomass cycle.

Earlier reports on the colour of the Great Lakes (Beeton, 1962; Putnam and Olson, 1961) are in general agreement with our observations. However, Beeton (1962) reported that orange light (590-610 nm) penetrated to the greatest depth in Lakes Erie and Ontario. In view of the examples given in this report and other work by this author (Thomson and Jerome, 1974) it seems that Beeton's measurements must have been located in an area where

Table 4. Dominant wavelengths for upwelling light at a depth of 1 metre, Lake Superior, July 1973

Station	Chlorophyll* µg/1	λ_D (nm)	Solar elevation (°)	% Transmittance at 1 metre
31	1.2	553	62	55
45	1.2	496	34	59
47	0.9	494	55	62
49	0.9	494	62	66
50	0.8	498	64	59
51	0.6	500	33	64
52	0.8	496	25	64
53	1.2	495	18	61
70	0.5	494	57	73
90	1.4	529	63	48
92	1.2	492	54	57
95	–	495	15	63
109	1.3	494	57	63
113	0.9	498	64	63
133	1.2	502	62	57
135	1.4	512	54	49
137	1.4	515	31	51
139	1.2	554	55	36
142	1.6	537	25	48

*Chlorophyll data is for a 0-20 m integrated sample.

Table 5. Lake Superior optical data, September 1973

Station	Depth (m)	λ_D (nm)	% Purity	Chlorophyll* µg/1	% Transmittance at 1 metre	
43	4	505	12	1.5	64	Downwelling
	12	505	35			Θ = 24°
	20	505	47			
68	1	570	17	2.0	58	Downwelling
	4	515	17			Θ = 36°
	16	515	38			
	20	530	46			
113	1	500	6	1.4	55	Downwelling
	4	510	14			Θ = 18°
	8	510	24			
169	1	500	7	1.2	64	Downwelling
	4	500	16			Θ = 47°
	8	520	20			
	12	515	30			
165	1	560	13	1.1	47	Downwelling
	4	550	30			Θ = 34°
218	1	560	15	2.0	41	Downwelling
	2	560	30			Θ = 31°
	4	560	42			
	8	555	62			
221	1	565	14	2.2	17	Downwelling
	2	565	36			Θ = 15°
	4	565	55			

*Chlorophyll data is for a 0-20 m integrated sample.
Θ is solar elevation.

sediment loading would influence the results and hence his figures are not representative of Lake Ontario or Lake Erie as a whole.

An important consideration of an optical colour analysis, such as described here, compared to a system such as the Forel colours is that the colour assessed is not matched to an artificial solution, but is the colour due to the *in situ* absorption and scattering properties of the water body. Further, this optical technique is based on well-defined and internationally accepted physical parameters.

In conclusion, it is encouraging that these experiments indicate the importance of optical measurements as a water quality indicator for the Great Lakes. The fact that *in situ* water colour is also a limnological parameter should be of impòrtance to workers interested in the measurement of water colour by remote sensing techniques.

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