

## SOLAR RADIATION AND ITS PENETRATION IN A TROPICAL ESTUARY

S. Z. QASIM, P. M. A. BHATTATHIRI, and S. A. H. ABIDI

*Biological Oceanography Division, National Institute of Oceanography, Ernakulam, South India*

**Abstract:** The Cochin Backwater which is an estuarine area on the west coast of India receives maximum solar radiation from December to March and minimum from June to September. During the monsoon months the estuary becomes highly turbid as a result of the inflow of a considerable amount of fresh water. Seasonal changes in the attenuation coefficient showed that light penetration is small throughout the year and least during the monsoon months. No relationship was found between the attenuation coefficient and amount of suspended matter. The upward scattering of light in the estuary ranged from 2–8 % of the incident illumination and the transmission of surface light at Secchi depth was about 23 %. The compensation depth in the estuary varied from 2.5–5 m and the zone of optimum illumination for maximum photosynthesis lay between 0–1.5 m.

### INTRODUCTION

The shallow semi-enclosed tropical estuary located along Lat.  $9^{\circ}58'N$  and Long.  $76^{\circ}15'E$  and commonly called the 'Cochin Backwater(s)', has a total area of about 200 square miles. It is one of the largest estuaries of India. On the western side it is permanently connected with the Arabian Sea by a narrow channel, about 450 m wide, which forms the main entrance to the Cochin harbour. Two large rivers, namely, the Periyar on the north, and the Pampa on the south, flow into it. A brief outline of the general hydrographical conditions of this estuary has been reported earlier (Qasim & Reddy, 1967). The chief characteristics, however, of the estuary are that during the monsoon months it receives a considerable amount of fresh water from the rivers and other sources and becomes highly turbid. The total annual rainfall of the Cochin area is about 3200 mm, of which nearly 75 % occurs during the period May–September. In the estuary, salinity variations from place to place and from surface to bottom are very wide. The onset of S.W. monsoon and its duration may, however, vary from year to year.

The work on solar radiation and its related aspects began in April 1965 as part of a programme on the hydrography of the Cochin Backwater. Fig. 1 shows the upper reaches of the estuary which are close to the sea and where observations on light penetration were made. In all, four stations (see Fig. 1), spread over a distance of about 15 km, were worked. Station 1, which is in the channel, close to the harbour, had a depth of 12 m, whereas the other three stations were shallower with depths ranging from 5–7 m. The bottom of the estuary is muddy. The tidal amplitude is about 1 m in the harbour area, decreasing to less than 1 m at Station 4. The area is a centre of human activity; besides incoming and outgoing shipping, there is a regular ferry service from the mainland to various thickly populated islands situated

within the estuary. A number of drains and sewage outlets flow into the estuary making the water in certain parts intensely polluted.

Although published accounts on solar radiation penetrating the oceans are numerous, reliable underwater measurements are few. Much of the earlier work

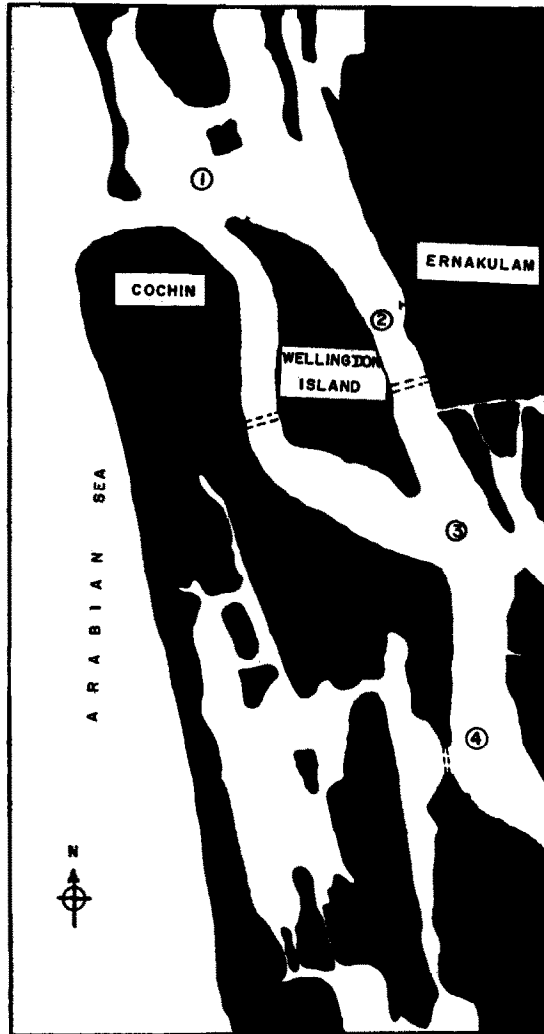


Fig. 1. Map showing the upper reaches of the estuary (Cochin Backwater) with its main connections with the Arabian Sea. Open circles indicate the four stations where observations on light penetration were made.

connected with methodology and optics of the sea has been comprehensively reviewed by Jerlov (1963) and that which has a direct bearing on photosynthetic productivity by Strickland (1958). Despite the acknowledged importance of surface and sub-

marine radiation, however, only a few studies have been undertaken on the light conditions in tropical waters, especially those of the Indian regions. The only investigations in the Indian Ocean in which submarine illumination has been included are those of Rangarajan (1959), working at the inshore waters of the Bay of Bengal, and Clarke & Kelly (1964) working in the western Indian Ocean. Determinations of the transparency of the water using a Secchi disk, have been made by Prasad (1952) and Rao (1958) in the Bay of Bengal. No previous information is available on other parts of the Arabian Sea.

#### PROCEDURE AND METHODS

The amount of daily illumination falling on the surface was measured by taking two-hourly readings with a lux-meter throughout the day, from sunrise to sunset, under different light conditions of the year. The lux-meter used was Dr. B. Lange's, Type II, having a selenium photo-element and a microammeter calibrated in lux. These readings were averaged to find the total illumination per day. Since considerable variation existed in the illumination throughout the year, depending upon how much the sun was obscured by clouds or atmospheric dust, the observations on the total daily illumination were adjusted according to total sunshine per day. Thus, when the sunshine hours were 10–12, the amount of daily illumination falling on the surface was approximately 500–700 kilolux-h (average 600 kilolux-h) and for 8–10 h of sunshine the average daily illumination was about 500 kilolux-h, and so on. From the daily illumination factors for the duration of sunshine so obtained (see Table I), the sunshine hours of each day were converted into light energy hours and pooled to find the arithmetic mean for each month.

The measurements of light penetration were made at fortnightly intervals by suspending the same lux-meter to various depths. The instrument had a range 0–100 000 lux and was particularly sensitive to the entire visible range of sun- and sky-light, 300–750  $m\mu$ ; it gave a maximum response around 550  $m\mu$ . For measuring high ranges of illumination a special grey filter with a light absorption factor 100 was used. All underwater measurements were made at about midday with customary precautions and expressed in readings of the lux-meter. Special precaution was taken to ensure that during the measurements at different depths the daylight should be steady and on all occasions when the sun was obscured by passing cloud, the readings were discarded. The decrease in illumination at each metre depth was expressed as the vertical attenuation coefficient,

$$k = 2.3 \frac{\log I_1 - \log I_2}{d_2 - d_1}, \quad (1)$$

where  $k$  is the attenuation coefficient and  $I_1$  and  $I_2$  are illuminations at depths  $d_1$  and  $d_2$ .

Transparency measurements were made with a Secchi disk, 20 cm in diameter,

and the illumination at the depth where the Secchi disk disappeared was noted on the photometer.

## RESULTS

### SOLAR RADIATION

Table I gives the percentage frequency of days in relation to sunshine hours throughout the year and the average daily illumination. As can be seen from the Table, very bright days with 10–12 h and 8–10 h of sunshine are most frequent during the year. Less bright days, with 6–8 and 4–6 h of sunshine, and cloudy days with 2–4 and 0–2 h of sunshine, are relatively few. The average daily illumination decreases with lesser number of sunshine hours and on very cloudy days it is about 150 kilolux-h.

TABLE I

Percentage occurrence of days corresponding to sunshine hours and intensity of illumination during 1965–66 at Cochin.

Daily sunshine, hours	10–12	8–10	6–8	4–6	2–4	0–2
Percentage occurrence of days in a year	31.2	20.2	15.1	9.6	8.5	15.4
Range in illumination (kilolux-h)	500–700	450–550	400–500	250–350	200–300	100–200
Average daily illumination (kilolux-h)	600	500	450	300	250	150
Average daily radiation (g cal/cm <sup>2</sup> /day)	626	522	470	313	261	157

The relation between daily illumination and total radiation is also shown in Table I (the conversion factor used is 57.5 kilolux per g cal/cm<sup>2</sup>/min; Narasimhan & Kumar, 1965). The values of solar radiation received during the day in different months of the year under average atmospheric conditions are shown in Fig. 2, from which it is seen that the total solar radiation progressively decreases from February to June and increases thereafter from July to January. This may be attributed to the number of hours of sunshine and degree of cloudiness in various months. The average solar radiation, however, received per day from November to February is twice that received in June and July. This is in marked contrast to higher latitudes where the solar radiation in summer months may be 10–20 or even 30 times as high as in the winter months (Atkins, 1938; Steemann Nielsen & Hansen, 1961). The important point worth noting is that the conventional seasons such as winter, spring, summer and autumn, which are associated with marked fluctuations in daily temperature, length of the day and hours of sunshine are not applicable in the tropics. Here the attenuation of radiation is mainly dependent on cloudiness or dust and vapour content of the atmosphere. Thus, the maximum solar radiation found during January

and February corresponds to the winter minimum of higher latitudes. But even in these months, on an overcast day, the radiation value for that particular day may fall to near the minimum, *i.e.* 150 kilolux-h. Similarly the minimum of the Cochin area during the southwest monsoon (June-July) corresponds to the maximum radiation of the temperate summer. Here again on an exceptionally clear day the solar radiation may reach almost the maximum value (600 kilolux-h). Harvey (1960)

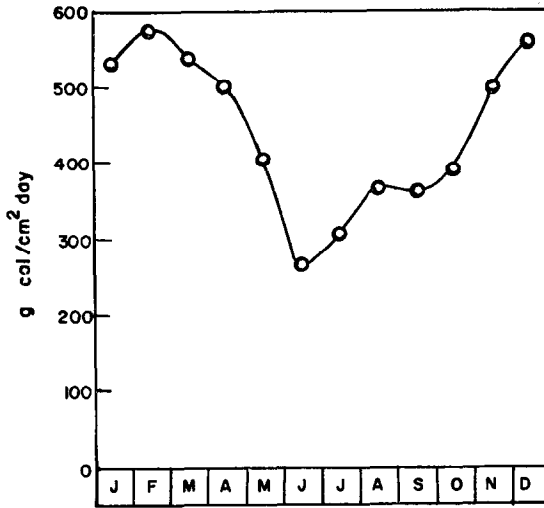


Fig. 2. Average monthly values of solar radiation at Cochin during 1965-66.

gives the daily illumination for bright days in the tropics as 600 kilolux-h. Taking into consideration all seasons, the average radiation in the Cochin area falls approximately within a range 250-550 g cal/cm<sup>2</sup>/day.

#### LIGHT PENETRATION

Since the light penetration in the estuary is greatly reduced because of high turbidity it was considered desirable, for purposes of standardization, to conduct an experiment using different makes of photometer and see whether all the instruments gave similar results. This experiment was conducted on January 3rd, 1966, and the photometers used were the lux-meter described earlier (p. 89); Weston 865-RR (Whitney) with a microammeter and graded neutral density filters; and a Tinsley's ratio-meter with matched deck photocell and null-method read out. The results of this experiment are given in Fig. 3, from which it is clear that all the three instruments gave similar results. The slight differences obtained were probably because of the differential spectral sensitivity of the instruments. At 1 m the illumination was reduced to 40-50 %; at 2 m 15-20 %; 3 m, 5-6 %; 4 m, 1.5-2.5 % and at 5 m, 0.5-1 %; below 0.5 m the mean attenuation coefficients for the three instruments were: Lux-meter, 0.95; Weston, 0.98; and Tinsley's, 0.99.

Monthly data for the attenuation coefficients ( $k$ ) at various depths corresponding to various stations are given in Table II from which it may be seen that throughout the observations the  $k$  values were very high; Cooper & Milne (1938) report even

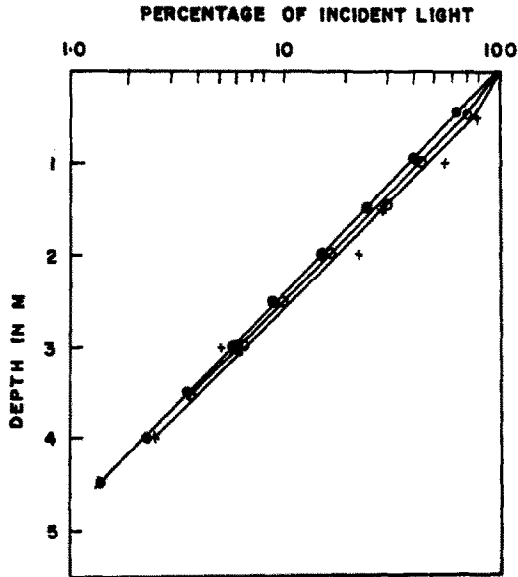


Fig. 3. Penetration of light in Cochin Backwater as shown by three different instruments on January 3rd, 1966. ● Lux-meter; + Weston 865-RR; ○ Tinsley's ratio-meter.

higher values from Tamar estuary. From Table II there is no evidence to suggest that the coefficients increase or decrease from one station to the other or from surface to the bottom, except on few occasions when some opaque patches caused the

TABLE  
Seasonal variation in attenuation coefficient

	Station 1 depth (m)					Station 2 depth (m)				
	1	2	3	4	5	1	2	3	4	5
Jan.	0.86	0.96	1.05	0.76	0.82	0.86	1.09	0.69	0.72	0.97
Feb.	1.20	1.20	1.24	1.22	0.98	0.96	0.87	1.01	0.98	0.70
Mar.	1.38	2.23	0.72	1.10	1.05	1.04	1.04	1.07	0.99	1.18
Apr.	2.12	4.14	—	—	—	1.54	1.62	1.73	2.14	—
May	1.52	1.74	1.51	1.73	1.61	5.54	—	—	—	—
June	1.22	0.94	0.94	—	—	1.38	1.08	1.22	1.71	0.81
July	2.77	3.49	—	—	—	1.93	1.57	0.93	0.29	1.10
Aug.	1.82	1.05	1.05	1.05	1.05	—	—	—	—	—
Sept.	1.76	1.74	1.44	1.43	1.45	1.81	1.38	1.40	0.94	1.46
Oct.	1.15	1.30	1.45	1.50	1.24	1.16	1.62	0.87	1.20	1.09
Nov.	1.77	1.86	1.48	1.32	1.38	1.54	1.36	0.96	0.92	1.20
Dec.	1.43	1.92	1.76	1.79	—	1.43	1.72	1.27	1.07	1.31

coefficient to increase or decrease rather abruptly. This indicates that turbidity in the estuary is more or less homogeneous. Since the changes in the  $k$  values from month to month were small, the data for the entire period of observation were pooled into three seasons, each of four months: February-May was taken as pre-monsoon; June-September as monsoon and October-January as post-monsoon. The data have been shown in Fig. 4 a-d, and may be summarized as follows. During the monsoon months, because of the high rainfall, the water becomes highly turbid and the light at all stations is reduced to about 17-22 % at 1 m and to about 1 % at 3 m (mean  $k = 1.37$ ). In the post-monsoon months the light penetration increases to 30-35 % at 1 m and 1 % at 4 m (mean  $k = 1.18$ ), but in the pre-monsoon months it falls again to 22-26 % at 1 m and < 1 % at 4 m (mean  $k = 1.36$ ), except at Station 4 where progressive clearing of the water increases the light penetration in the pre-monsoon months (mean  $k = 1.04$ ).

The relation between attenuation coefficient ( $k$ ) and seston (suspended matter) is shown in Fig. 5. The values of  $k$  in the figure refer to those calculated from the photometer readings taken in the field and the corresponding values of seston were obtained by filtering a known quantity of water taken from the same depth at which the illumination was measured and accurately weighing the dried filters before and after filtration. It may be seen from the figure that there is no correlation between these two values ( $r = +0.31$ ). This suggests the presence of large and variable quantities of suspended particles. Jones & Wills (1956) using a parallel beam transmittance meter found a linear relation between  $k$  and lower concentrations of seston up to 10 mg/l, but at higher concentrations the same relationship did not hold since the increase in  $k$  became less steep. Such a variation was attributed by these authors to the nature and size of particles in suspension. Although the method of drawing relationship between  $k$  and seston content for the Cochin Backwater was somewhat

## II

( $k$ ) with depth at various stations

Station 3 depth (m)					Station 4 depth (m)				
1	2	3	4	5	1	2	3	4	5
1.06	0.82	0.59	0.74	0.73	0.96	0.79	1.00	0.84	0.95
1.22	1.10	1.25	1.42	1.39	1.25	0.95	1.13	1.01	1.40
1.19	1.32	1.94	1.38	1.76	1.01	1.10	0.67	1.01	1.00
0.99	1.12	0.91	0.85	0.56	0.99	0.86	1.01	0.98	0.95
2.86	4.15	—	—	—	3.40	3.39	—	—	—
1.70	1.15	1.43	1.62	1.32	1.20	0.64	0.96	1.10	0.98
1.47	1.72	1.55	1.76	2.01	1.70	2.15	1.57	1.38	1.30
2.43	2.26	2.56	—	—	2.08	2.20	2.62	—	—
1.61	1.11	0.61	0.41	0.82	1.24	1.47	1.11	0.89	0.96
1.96	1.90	0.91	1.91	—	2.78	2.01	1.42	1.60	—
1.77	1.18	1.33	0.94	1.15	1.29	1.12	1.39	1.24	1.21
1.80	1.89	1.18	1.07	1.51	—	2.15	—	—	1.—

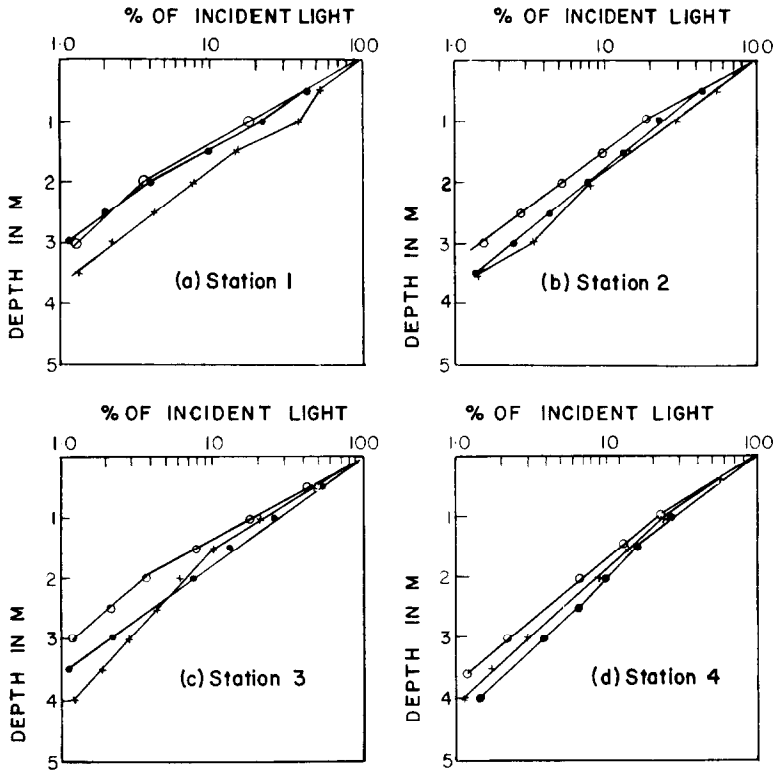


Fig. 4. Seasonal changes in light penetration at four different stations of Cochin Backwater during 1965-66. The year has been divided into three seasons; June-September as monsoon, October-January as post-monsoon and February-May as pre-monsoon. ○ monsoon; + post-monsoon; ● pre-monsoon.

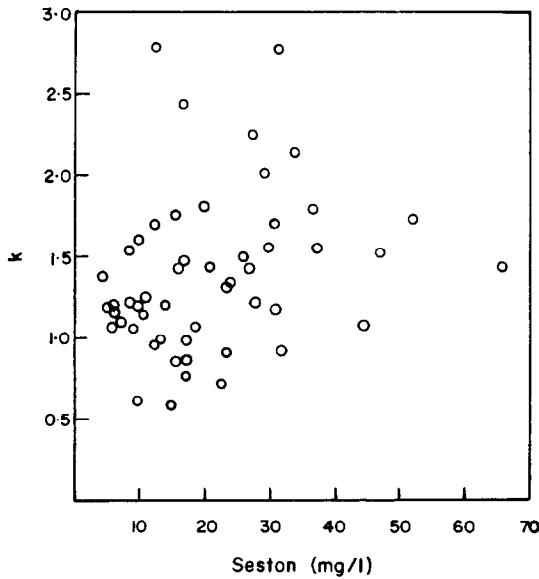


Fig. 5. Relation between attenuation coefficient ( $k$ ) and seston (suspended matter).



indirect, lack of correlation indicates that the explanation given by Jones & Wills (1956) may be valid, since there the seston content was always excessive (seldom less than 10 mg/l) with considerable variation in particle size.

The other factor which may obscure the relationship between  $k$  and seston is the presence of unfilterable Gelbstoff (Kalle, 1966). These substances, which in part at least originate as decomposition products of plant material, lead to rapid attenuation of light (Jerlov, 1951). In estuaries and inshore waters these yellow substances are found in excessive quantities, for they are associated with the dissolved matter brought down by the rivers (Jerlov, 1951), and their selective absorption of light is far more important than the influence of seston (Jerlov, 1955). The presence of Gelbstoff in the Cochin Backwater was demonstrated by measuring the absorption spectra of filtered sea water at 10  $m\mu$  intervals (Kalle, 1966) on a Unicam SP 500 spectrophotometer. Maximum absorption occurred in the range of 400–500  $m\mu$  and minimum in the range of 600–700  $m\mu$ , thus confirming the presence of very large quantities of yellow matter in the estuary.

#### OPACITY OF WATER AND UPWARDSCATTERING

Secchi disk extinctions as an index of opacity of water have been plotted in Fig. 6 in relation to percentage transmission of surface illumination. It can be seen from

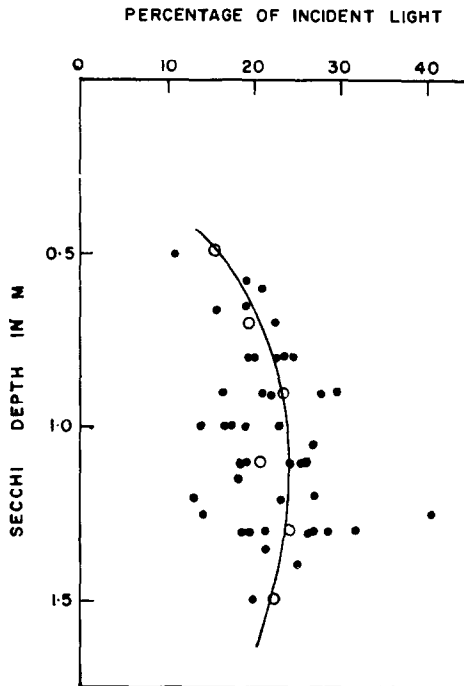


Fig. 6. Secchi depth plotted against percentage transmission of surface illumination at Secchi extinction depth. ● combined data of all stations; ○ average of 20-cm interval.

this figure that the values fall within a range of 15–25 % (mean 22.6 %, S.D.  $\pm 5.3$ ). This is much higher than the values reported for clear waters (Poole & Atkins, 1928; Beeton, 1958) and falls close to the range of transmission reported by Gall (1949). When the turbidity is high, the great reduction in the Secchi depth seems associated with an increase in percentage transmission of illumination, *i.e.*, more light is required to see the disk at lower depths.

Taking the transmission of surface illumination where the Secchi disk disappears as 22.6 %, the relation of attenuation coefficient ( $k$ ) and the Secchi depth  $D$  may be obtained by substituting  $I_1 = 100$  and  $I_2 = 22.6$  in equation (1) to give,

$$k \sim 1.5/D. \quad (2)$$

The other factor which may lead to a higher transmission ratio at Secchi depth is the upward scattering. The ratio of upward scattering to downward illumination in clear waters has been found to range from 2–5 % (Strickland, 1958) or 3–6 % (Ryther, 1959).

In the Cochin Backwater the angular distribution of light was measured at mid-day. The angles of photometer looking upwards and downwards were taken as  $0^\circ$  and  $180^\circ$ , respectively. The ratios of the illumination at various angles to downward illumination at given depths are given in Table III, from which it may be seen that the ratios decrease when the angle of photometer is increased and at all angles except when the upward-scattered light was measured, *i.e.*, when the photometer was at  $180^\circ$ , the ratios gradually increase with depth. The ratio of upward to downward

TABLE III

Angular distribution of light and upward scattering: the values indicate illumination-ratio (%) at various angles to downward illumination at 0–4 m depth.

Depth (m)	Percentage ratio			
	$45^\circ/0^\circ$	$90^\circ/0^\circ$	$135^\circ/0^\circ$	$180^\circ/0^\circ$
0.1	—	—	—	8
0.2	80	32	11	8
0.3	86	34	11	7
0.4	90	37	11	7
0.5	83	39	12	6
0.6	92	42	12	5
0.7	88	44	13	5
0.8	96	47	13	5
0.9	104	50	13	5
1.0	104	48	14	4
1.1	110	—	—	—
1.5	108	38	15	5
2.0	100	33	13	3
2.5	95	33	16	3
3.0	86	31	16	2
3.5	135	40	17	2
4.0	83	40	17	—

illumination ranged from 8–2 % (average 5 %) within 0–3 m. Although the average value is not very different from similar ratios reported by Clarke (1936) and Atkins & Poole (1940), the range appears to be appreciably higher than that reported in less turbid waters and possibly indicates that the upward scattering in the wavelength range 300–750  $m\mu$ , is greatly influenced by the nature and amount of particulate matter present in the water – an explanation which requires further investigation in the light of Jerlov's (1963, 1965) findings based on irradiance measurements that a nonselective scattering is produced in turbid waters in contrast to selective upward irradiance in clear waters caused by molecular scattering. It is, however, of interest to note that in the estuary the upward scattering was particularly high (8–5 %) within one metre, which was reduced, rather abruptly, to 2 % within the next two metres (Table III). The reason for this seems to be that the uppermost layer of the estuary, besides being diluted by the fresh water is also periodically enriched by sea water and hence the characteristics of its suspended and dissolved matter are rapidly changing. The light absorption and scattering in the uppermost layer would, therefore, largely depend upon the conditions at the time of measurements and perhaps for this reason the results appear to be somewhat less consistent than would be expected in uniformly turbid or clear waters.

Taking 5 % as an average for the upward-scattered light in the Backwater, this would mean that the Secchi disk will disappear at a depth from where the illumination reaching the observer's eye is reduced to approximately 5 %, which is equal to the ratio of upwards to downward illumination. This assumption is based on disregarding the distance from the surface to the observer's eye which in the present case was small (1–2 ft) since the observations were made from a dinghy; therefore, substituting  $I_1 = 100$  and  $I_2 = 5$  and  $2D$  instead of  $D$ , for the light travels twice from the disk to the observer's eye, in equation (1)

$$k \sim 1.5/D \quad (3)$$

It is, therefore, clear that in highly turbid waters the empirical relation between Secchi disk depth and  $k$  based on percentage transmission of surface illumination (equation 2) and the ratio of upwards to downward illumination (equation 3) agree closely and this relationship may possibly hold true for all very turbid estuaries and lakes. The expression  $k = 1.7/D$  of Poole & Atkins (1929) based on data from the English channel, where the Secchi disk extinction was at 15.8 % of the surface illumination, seems applicable to all moderately clear waters, but in very clear waters the relationship  $k = 1.9/D$  seems more appropriate (Strickland, 1958).

Table IV shows the average values of  $k$  obtained from the photometer readings and those computed from the Secchi disk readings by the expression of Poole & Atkins and also by the present relation. It is evident from the Table that the computed values by the present expression fall close to the observed values of  $k$ .

A plot of the reciprocal of Secchi disk depth and the mean  $k$  (Fig. 7) gave a rela-

tionship which was similar to that shown by Graham (1966); the regression line is given by:

$$y = 0.36x + 0.47. \tag{4}$$

COMPENSATION DEPTH

The compensation depth of the euphotic zone is defined as the depth where

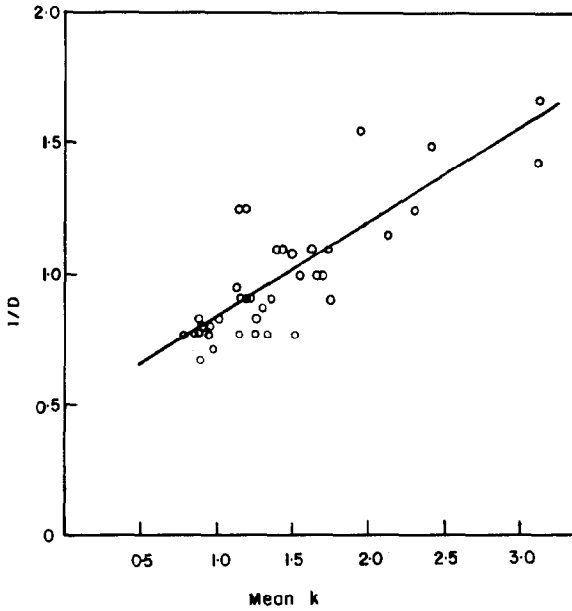


Fig. 7. The relation between reciprocal of Secchi depth ( $1/D$ ) and the attenuation coefficient ( $k$ ).

TAB

Comparison of observed and computed values of  $k$ ; observed values refer

	Station 1			Station 2		
	Observed (photocell)	Computed $k = 1.7/D$ $k = 1.5/D$		Observed (photocell)	Computed $k = 1.7/D$ $k = 1.5/D$	
Jan.	0.89	1.31	1.15	0.87	1.31	1.15
Feb.	1.17	1.55	1.36	0.90	1.42	1.25
Mar.	1.30	1.48	1.30	1.06	—	—
Apr.	3.13	2.43	2.14	1.76	1.55	1.36
May	1.62	—	—	5.54	—	—
June	1.02	1.42	1.25	1.24	1.55	1.36
July	3.13	2.83	2.50	1.38	2.13	1.88
Aug.	1.20	2.13	1.88	—	—	—
Sept.	1.56	1.70	1.50	1.40	1.89	1.67
Oct.	1.33	1.31	1.15	1.19	1.55	1.36
Nov.	1.56	1.70	1.50	1.20	1.55	1.36
Dec.	1.73	1.89	1.67	1.36	1.55	1.36

photosynthesis and respiration just balance resulting in no production and no increase in organic matter over a day (Strickland, 1958). At this depth the illumination is reduced to about 1 % of that at the surface (Steemann Nielsen & Hansen, 1961), but depending upon temperature and other factors this might well be anything from 0.2 to 2.0 %. In the Cochin Backwater the seasonal changes in compensation depth

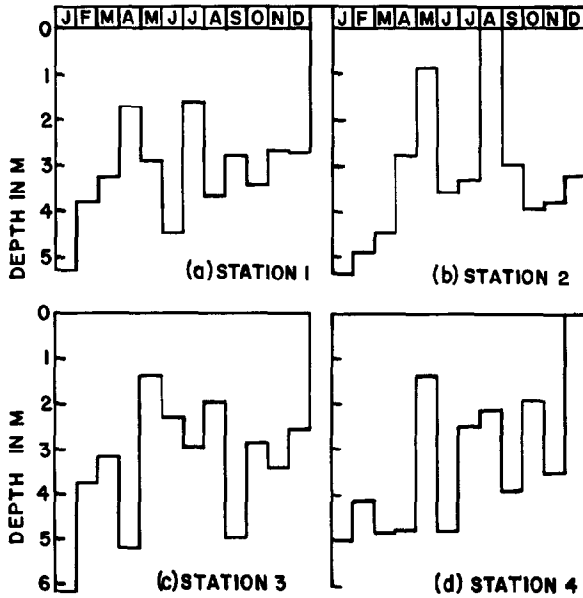


Fig. 8. Seasonal changes in the compensation depth at the four different stations (a, b, c, d) of Cochin Backwater from August 1965-July 1966.

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near  $k$  from photometer and computed values from Secchi disk readings.

Station 3			Station 4		
Observed photocell)	Computed		Observed (photocell)	Computed	
	$k = 1.7/D$	$k = 1.5/D$		$k = 1.7/D$	$k = 1.5/D$
0.79	1.31	1.15	0.91	—	—
1.28	—	—	1.15	1.31	1.15
1.52	1.31	1.15	0.96	1.36	1.20
0.89	1.13	1.00	0.96	1.31	1.15
3.50	—	—	3.40	—	—
1.44	1.89	1.67	0.98	1.21	1.07
1.70	1.70	1.50	1.62	1.89	1.67
2.42	2.83	2.50	2.30	2.13	1.88
0.91	1.89	1.67	1.13	1.62	1.43
1.67	1.70	1.50	1.95	2.61	2.31
1.27	1.42	1.25	1.95	1.31	1.15
1.50	1.93	1.70	2.15	2.02	1.79

as determined by the average transmission of incident illumination are given in Fig. 8a-d for the various stations. As may be seen from the Figure, because of the high turbidity, the compensation depth never exceeded 5-6 m. Lowest depths were recorded during the monsoon months when heavy rainfall brought in an excessive load of silt and stirred up the suspended matter. In the post-monsoon months, due to progressive clearing of the water, the compensation depth increased and reached its maximum in January and February. At Station 1, which is close to the harbour, there is constant stirring up of sediments due to tidal action and movement of ships, so that the clearing of water in the post and pre-monsoon months was less marked than at other stations. In April and May when the pre-monsoon rains set in, the compensation depth decreases suddenly. In June the unexpected increase in the compensation depth at all stations was because the monsoon was delayed by a few weeks in 1966.

In Fig. 9 the compensation depth is plotted against the Secchi disk depth. It may be seen from the Figure that despite much scatter in the points the fitted curve

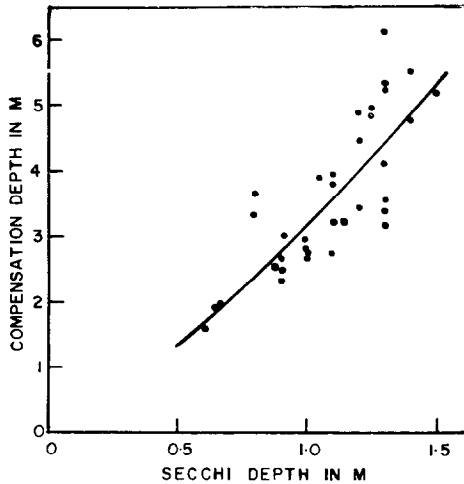


Fig. 9. The relation between Secchi depth and compensation depth; the latter has been taken as 1% of surface illumination.

indicates that the relationship between Secchi disk depth and compensation depth approximates to linear up to 3 m, above which the increase in Secchi disk depth becomes somewhat less than the increase in compensation depth as determined by the photocell. When the turbidity is high the disk disappears quickly and rather suddenly and therefore a fairly accurate determination of Secchi disk depth is easy, but when the water is clearer, despite all precautions, discrepancies arise in determining the exact depth of the Secchi disk extinction. Errors amounting to 2 ft have been observed in clear lakes (Beeton, 1958) and presumably in very clear oceanic waters discrepancies as great as several metres may be encountered. The compensation

depth has been reported to vary with the Secchi disk readings by a factor 3-4 (Strickland, 1965). In the present case the relation has the form

$$y = 3.16 x^{1.26} \tag{5}$$

DISCUSSION

From the total solar radiation falling on the surface, the fractions of the visible portion of the spectrum reaching various depths in the estuary are shown in Fig. 10.

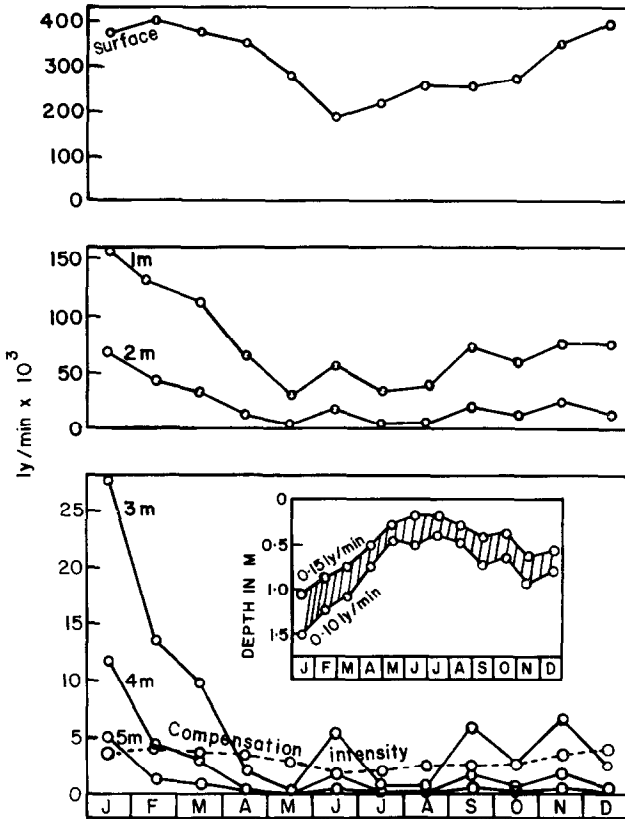


Fig. 10. Total solar radiation falling at the surface of Cochin Backwater during 1965-66 and the fractions of it reaching each metre depth (1-5). The inset figure shows the range in the optimum illumination (0.10-0.15 ly/min) available for maximum photosynthesis in the various months. The compensation intensity curve (broken line) has also been drawn in the lower part of the figure.

These have been computed from the pooled values of attenuation coefficients of all four stations (see Table II). Photosynthesis by phytoplankton is a function of illumination, and the optimum radiation required for maximum growth of a mixed phytoplankton population is believed to be 0.05-0.15 ly/min or g cal/cm<sup>2</sup>/minute

(Strickland, 1958). For Chlorophyta, diatoms, and dinoflagellates, Ryther (1956) gives a range 0.03–0.16 ly/minute and for a shade- and light-adapted coccolithophore, *Syracosphaera carterae*, the range is 0.1–0.2 ly/minute (McAllister, 1961). For tropical phytoplankton, 30–50 % of the surface illumination is believed to be the optimum illumination (Stemann Nielsen & Jensen, 1957). In bacteria-free cultures of *Skeletonema costatum* and several species of dinoflagellates, maximum growth and photosynthesis have been found to occur at about 0.1 ly/minute (McAllister, Shah & Strickland, 1964). From these data, taking 0.1–0.15 ly/minute or 30–50 % of the surface illumination as a reasonable estimate of the optimum light conditions, the zone where maximum photosynthesis could possibly occur in relation to this illumination-range in the estuary is shown in Fig. 10. This is perhaps a close approximation to the optimum illumination and not to total energy required for photosynthesis. It is clear from the Figure that in January and February when the water is relatively less turbid, optimum illumination is found at about 1–1.5 m; with increase in turbidity this level gradually moves up, close to the surface, and in June and July it lies between the surface and 1 m.

At the compensation point intensity, (*i.e.*, the lower limit of light where respiration just balances photosynthesis) the energy flux is reduced to  $2 \times 10^{-3}$  to  $5 \times 10^{-3}$  ly/minute (Strickland, 1958). The calculated value, 1 % of the surface radiation (24 h mean), has also been plotted in Fig. 10 as a compensation intensity curve. This curve intersects the various other curves pertaining to the illumination available at 3–5 m. It may be seen from the Figure that in January the compensation intensity is found at about 5 m whereas in other months it ranges from 2–4 m. This agrees well with the more direct measurements of compensation depths described earlier (p. 98).

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