THE ECOLOGY OF THE TAMAR ESTUARY
V. UNDER-WATER ILLUMINATION. REVISION OF DATA FOR RED LIGHT

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When the Pulfrich photometer is used to measure absorption of light by a turbid estuarine or sea water, the true extinction coefficient for light of a given wave-length

$$\mu_{SW} = \mu_M + \mu_{DW},$$

where μ_M is the extinction coefficient as measured and μ_{DW} is the extinction coefficient of the distilled water used in the comparison tube of the photometer. When our paper on under-water illumination in the Tamar Estuary was prepared (Cooper & Milne, 1938), we knew of no modern data on the extinction coefficient of distilled water in the deep red, except those of Lange & Schusterius (1932) which we unjustifiably rejected. James (1938) has since published exhaustive data of his own and gives, in full, results obtained by Prof. J. R. Collins and Dr Ernst Ganz. These leave no doubt that between 700 and 760 mμ the coefficient rises very steeply from about 0·6 to 2·6, and that the distilled water correction which we applied to our results was in serious error. This spectral region is also one in which visual sensitivity is decreasing rapidly. These two factors much favour the transmission and visual perception of light of shorter wave-length. However, the two red filters, S 72 and S 75, equally strongly favour the transmission of light of longer wave-length. Average extinction coefficients cannot be evaluated by simple inspection. Using the data of James, of Collins and of Ganz we have worked them out for the conditions of our experiments.

Effective Extinction Coefficient of Distilled Water Measured by the Red Filters of the Pulfrich Photometer

Consider a light source of known energy distribution and let J_λ represent the relative energy at a given wave-length. After passing through a filter having a transmission c_λ, the relative energy will be reduced to $c_\lambda J_\lambda$. If V_λ represents relative visibility (i.e. the relation between luminous sensation as perceived by the eye and radiant energy), the visual sensation produced by this transmitted light will be $c_\lambda J_\lambda V_\lambda$. The transmission coefficients of the filters expressed as percentages have been supplied by Messrs Carl Zeiss (cf. Cooper & Milne, 1938, Fig. 1). Relative visibility has been taken from

Smithsonian Physical Tables (1933, 8th revised ed.), Table 346; $c_\lambda J_\lambda V_\lambda$ may be plotted against wave-length, and the area $\int_{\lambda_1}^{\lambda_2} c_\lambda J_\lambda V_\lambda \, d\lambda$ enclosed by the curve and the wave-length axis will provide a measure of the light sensation perceived by the observer's eye. It may be evaluated most conveniently with a planimeter.

Since in our work we used 0·25 m. absorption tubes, we have also calculated the relative energy of a narrow wave band, having extinction coefficient μ_λ, after passing through 0·25 m. of distilled water, $J_\lambda e^{-0\cdot25\mu_\lambda}$. This intensity also may be transmitted by the spectral filter and perceived by the eye so that the measure of light sensation will be $c_\lambda J_\lambda e^{-0\cdot25\mu_\lambda} V_\lambda$. This may be plotted on the same graph as $c_\lambda J_\lambda V_\lambda$. The ratio of the areas suffices to evaluate the logarithmic term in the expression

$$0{\cdot}25\,\mu_A = 2{\cdot}303 \log_{10} \frac{\int_{\lambda_1}^{\lambda_2} c_\lambda J_\lambda V_\lambda \, d\lambda}{\int_{\lambda_1}^{\lambda_2} c_\lambda J_\lambda e^{-0\cdot25\mu_\lambda} V_\lambda \, d\lambda}.$$

The value obtained for μ_A is the effective extinction coefficient of distilled water for a given filter, which is required as our correction factor. It applies only for 0·25 m. tubes.

Since we do not know the spectral energy distribution of the Nitra lamp supplied with the Pulfrich photometer, we have calculated the effective extinction coefficient, first from Abbot's mean noon sunlight data (Seventh Internat. Congress of Photography, 1929), secondly for light having an equal energy spectrum over the range of wave-length considered, and thirdly for a light source having a colour temperature of 2800° K. (Table I). Considerable latitude in the colour composition of the light source may be tolerated. Much more important are the great variations of the extinction coefficients based on the determinations of different observers and of relative visibility with wave-length. Furthermore, in this region considerable personal idiosyncracy in relative visibility is to be expected.

James (1938, p. 37) discusses the variable coefficients for distilled water found by different observers. These cannot be attributed to errors of measurement and must be due to some variable property of distilled water itself, possibly minute traces of impurities or variable degree of association of the water molecules dependent on the previous history of the water. Whatever the cause, any ordinary laboratory sample of distilled water is likely to show variability at least as great. Below 600 mμ the coefficient is small compared with the measurements on a fairly turbid estuarine water, so that some degree of uncertainty is of little consequence. Above 650 mμ matters are very different. The best we can do is to apply an average effective extinction coefficient as correction factor, as suggested in Table I.

In relatively transparent ocean water, accurate measurement of the extinction coefficients for blue, green and yellow light requires a water column much longer than can conveniently be accommodated by the Pulfrich photometer. Even if this difficulty could be overcome, the correction terms for the absorption of light by ordinary laboratory samples of distilled water remain too uncertain for the method there to be of much value. Its utility is confined to fairly turbid inshore or estuarine waters.

TABLE I. EFFECTIVE EXTINCTION COEFFICIENT FOR RED LIGHT

Transmitted by 0·25 m. of distilled water and measured with the filters of the Pulfrich photometer

	Temperature ° C.	Type of spectrum	Particulars of filters		
Filter no.	...	...	S 75	S 72	S 61
Effective wave-band*, mμ	...	...	730–770	700–760	600–650
Centre of gravity of filter, mμ	...	...	750	729	619
			Effective extinction coefficient		
Calculated from data of:					
James (1938)	Room	Colour temperature 2800° K.	2·24	1·74	...
,,	,,	Equal energy	2·23	1·78	0·28
,,	,,	Mean noon sunlight	2·29	1·76	...
Collins (cit. James)	0·5	,, ,,	2·61	2·02	0·29†
,, ,,	26	,, ,,	2·79	2·14	...
Ganz (cit. James)	12	,, ,,	2·54	1·55	...
Values adopted as correction terms			2·5	1·8	0·28

* These are the limits within which the transmission exceeds one-half the maximum. For purposes of summation, transmissions exceeding one-tenth were included.

† Approximate value obtained by inspection (strictly for equal energy spectrum).

REVISION OF THE ORIGINAL DATA

A list of the numerical revisions made necessary by the change in our correction factors will be found at the end.

The revised values of the ratio μ_λ/μ_{470} for the S 61, S 72 and S 75 filters still show that very turbid waters transmitted red light as well as or better than blue. When μ_λ is graphed against μ_{470}, the relationship may be expressed surprisingly well by the linear equations given in Table II. The constant terms for the red filters are almost the same as those applied to correct for the absorption by distilled water. For the remaining filters similar terms would be quite small. The views expressed in the earlier paper as to the transmission of red light still apply up to about 680 or 700 mμ. Above this the molecules of water itself manifest strong absorption of light, and in fairly clear waters this is all important, but that part of the extinction coefficient, which was due to dissolved and suspended solids, was always least in the deep red. These factors work in opposition, and as a result the minimum extinction coefficient or maximum transmission for our more turbid waters was to be found around 600 mμ.

The ratios of the wave-length at the centre of gravity of the blue S 47 filter compared with the corresponding wave-lengths of the other filters, also given in Table II, show that that part of the extinction coefficient due to

TABLE II. RELATION BETWEEN EXTINCTION COEFFICIENTS AND WAVE-LENGTH

(Revision of original Table III)

Filter	Equation connecting μ and μ_{463}	Ratio of wave-length of blue filter to that of the others (at centres of gravity) $\frac{463}{\lambda}$
S 43	$\mu_{434} = 1{\cdot}11\,\mu_{463}$	1·07
S 47	$\mu_{463} = 1{\cdot}00\,\mu_{463}$	1·00
S 50	$\mu_{494} = 0{\cdot}92\,\mu_{463}$	0·94
S 53	$\mu_{530} = 0{\cdot}86\,\mu_{463}$	0·87
S 57	$\mu_{572} = 0{\cdot}82\,\mu_{463}$	0·81
S 61	$\mu_{619} = 0{\cdot}35 + 0{\cdot}73\,\mu_{463}$	0·75
S 72	$\mu_{729} = 1{\cdot}80 + 0{\cdot}68\,\mu_{463}$	0·64
S 75	$\mu_{750} = 2{\cdot}54 + 0{\cdot}64\,\mu_{463}$	0·62

suspensoids and possibly to matter in solution is inversely proportional to the first power of the wave-length. The relationship is sufficiently close that, if only one extinction coefficient were known, that for any other wave-length could be calculated with an accuracy sufficient for most practical purposes.

The absorption index, K, defined by the equation

$$\mu_{SW} - \mu_{DW} = \frac{4\pi K}{\lambda},$$

is a constant for each water; $\mu_{SW} - \mu_{DW}$ is, in effect, a measure of absorption by suspensoids.

The dependence of scattering of light by particles in sea water upon various powers of the wave-length has been discussed by Kalle (1938).

REVISED DATA (COOPER & MILNE, 1938)

P. 510, Table I: Extinction coefficients of distilled water: Accepted values for filters S 61, S 72 and S 75 are 0·28, 1·8 and 2·5 respectively.

P. 514, l. 26: *For* "($\mu_{500} = 5{\cdot}0$; $\mu_{720} = 3{\cdot}8$)" *read* "($\mu_{500} = 5{\cdot}0$; $\mu_{720} = 5{\cdot}3$)".

P. 514, Table II: For last line of figures, read:

μ_{720}	5·9	8·2	7·5

P. 515, ll. 1 and 2 from bottom: *Read:* "the intensity of red and blue light entering the water was cut down to one-thousandth within 0·5 and 0·6 m. respectively ($\mu = 13{\cdot}5$ and $16{\cdot}5$)."

P. 516, Fig. 3: The plots at 610, 720 and 750 mμ should be 0·1, 1·3 and 2·0 units higher respectively. A minimum extinction coefficient occurs at about 600 mμ in most cases.

P. 517, Table III: See p. 394.

Pp. 519 and 520, Figs. 4 and 5: All curves should show less relative energy in the dark red. The statement about preferential transmission of red light does not apply above about 680 mμ.

P. 522, Table IV.

DEPTH IN METRES AT WHICH INTENSITY OF RED LIGHT IS REDUCED TO 1 % OF THAT INCIDENT ON THE SURFACE

Assuming 15 % Surface Loss; $\mu d_1 = 4{\cdot}44$

Centre of gravity of filter mμ	Breakwater No. 1 Buoy	Drake's Island No. 1 Buoy	Hamoaze No. 1 Buoy	Hamoaze No. 7 Buoy	Hamoaze No. 15 Buoy	Neal Point Buoy
		February 18 1937. Spring tide. High water				
619	2·35	1·97	1·85	1·41	1·30	...
729	1·37	1·26	1·22	1·02	0·99	...
750	1·09	1·00	1·04	0·86	0·82	...
		February 16 1937. Spring tide. Low water				
619	1·93	1·95	1·10	0·78	0·53	0·35
729	1·33	1·25	0·89	0·69	0·48	0·33
750	1·04	1·07	0·76	0·60	0·46	0·35
		June 17 1937. Neap tide. High water				
619	3·86	4·27	3·06	2·48	2·54	2·48
729	1·77	1·78	1·60	1·42	1·40	1·39
750	1·38	1·40	1·27	1·18	1·19	1·15
		June 23 1937. Spring tide. Low water				
619	5·00	3·21	2·74	2·04	1·41	0·98
729	1·95	1·60	1·48	1·27	1·00	0·79
750	1·49	1·27	1·16	1·05	0·90	0·71

P. 525, Table V.

DAYLIGHT FACTORS AT BOUNDARIES OF ALGAL ZONES ON BUOYS

No correction for surface loss

	Zone I		Zone II	
	Plymouth Sound	Hamoaze No. 7 Buoy	Plymouth Sound	Hamoaze No. 7 Buoy
Depth of bottom of zone, m. ...	0·18	0·097	0·356	0·223
Daylight factor, %:				
June 17 (high water)	78·3	80·0	62·3	61·8
June 23 (low water)	76·4	77·8	59·2	56·5
February 18 (high water)	65·4	69·8	43·7	45·0
February 16 (low water)	60·9	52·4	37·7	23·3

TABLE VI. DAYLIGHT FACTORS AT BOTTOM OF TWO BUOYS (WITHIN ZONE III)

	Mallard Buoy (Plymouth Sound)			Hamoaze No. 7 Buoy		
Date and state of tide	Depth of bottom of buoy m.	Daylight factor %	Wave-length of maximum transmission mμ	Depth of bottom of buoy m.	Daylight factor %	Wave-length of maximum transmission mμ
June 17 (high water)	2·19	7·41	570	2·47	0·97	570
June 23 (low water)	2·19	5·51	570	2·47	0·35	600
February 18 (high water)	2·19	0·85	580	2·47	0·020	600
February 16 (low water)	2·19	0·34	620	2·47	0·000025	620

P. 524, Table VII. All the extinction coefficients given in the last column should be increased by 1·3.

P. 526, l. 3: *For* "0·36 and 17 m. (ratio 1 : 48)" *read* "0·33 and 17 m. (ratio 1 : 52)."

P. 526, Table in Summary: The values for red light (610–640 and 710–760 mμ) should be increased by 0·1 and 1·33 respectively.

SUMMARY

New values for the extinction coefficient of red light in distilled water require that published results for this coefficient in waters from the Tamar Estuary shall be increased by 0·1, 1·3 and 2·0 at 610, 720 and 750 mμ respectively. Earlier deductions as to the favourable transmission of red light in turbid estuarine waters apply only up to about 680 mμ. That part of the extinction coefficient due to suspensoids and colouring matter was inversely proportional to the first power of the wave-length. Other conclusions remain unaffected.

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