Predicting light penetration into river waters

Robert J. Davies-Colley[1] and John W. Nagels[1]

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[1] Lighting in rivers often needs to be quantified, particularly for modeling benthic plant growth, but is seldom measured because of difficulties associated with limited depth and strong currents. Therefore, methods for predicting light attenuation from river water quality data would be very useful. We used measurements of the diffuse light attenuation coefficient, K_d (m^{-1}), at 17 optically diverse rivers in New Zealand to develop simple empirical models of light penetration as functions of the beam attenuation coefficient at 550 nm, c_{550} (m^{-1}, an index of visual water clarity) and the light absorption coefficient of membrane filtrates at 340 nm, g_{340} (m^{-1}, an index of colored dissolved organic matter). The beam attenuation coefficient can be measured by beam transmissometer or estimated, as in this study, from black disc visibility observations. Alternatively, nephelometric turbidity, T_n (an index of light scattering), which is more commonly measured in water quality monitoring programs, can be used to predict K_d. The models performed satisfactorily when tested over a wide range of optical water quality (varying with flow) at one river site. We expect that these empirical models will have wide practical application for estimating light availability in rivers and streams.

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1. Introduction

[2] The behavior of light in water bodies has long been of interest to aquatic scientists concerned with photosynthesis of aquatic plants, behavior of aquatic animals, photochemical reactions in waters, recreational use of waters, and optical remote sensing of water quality. A valuable concept linking water optics to water quality is "optical water quality" [*Kirk*, 1988], the suitability of the water for use as determined by its optical properties.

[3] By far, the majority of the research on optical water quality has been done on standing waters, including lakes, but more particularly marine waters in which optical remote sensing applications continue to be a major driver. By comparison, the optics of flowing waters have been comparatively neglected [*Davies-Colley et al.*, 2003; *Julian et al.*, 2008a], although several contributions have been made on New Zealand rivers. For example, *Smith et al.* [1997], building on earlier work by *Davies-Colley and Close* [1990] and *Davies-Colley* [1990], summarized optical water quality data in relation to flow in 64 free-flowing rivers sampled routinely in New Zealand's National Rivers Water Quality Network (NRWQN). They showed that in accord with common observations, rivers are typically clear and low in colored dissolved organic matter (CDOM) at low flow but turbid and yellow in color at high flow. Most recently, *Julian et al.* [2008a] analyzed optical water quality changes in four contrasting rivers and showed that spatial trends are controlled mainly by channel network configuration while temporal variability depends mainly on flow.

[4] Despite the advances in characterization of rivers as regards routine optical water quality, no systematic attempt has been made, so far as we are aware, to characterize light penetration into a wide range of optical types of rivers. This is despite pioneering light attenuation measurements in rivers being reported 4 decades ago [*Westlake*, 1966]. Light penetration into large, strongly light-attenuating rivers has been measured as part of special studies [*Effler et al.*, 2005; *Gallegos*, 2005] but seldom on clear or small rivers where light attenuation is more difficult to measure and is perhaps perceived incorrectly as no problem [*Julian et al.*, 2008b].

[5] Estimates of light penetration into rivers are often needed for diverse purposes, including modeling primary production and predicting die off (mainly due to sunlight exposure) of microorganisms of health concern. Light penetration in waters is fairly readily measured by deploying light sensors at different depths so as to construct a depth profile of lighting. However, there are practical difficulties in rivers and streams owing to limited depth and fast currents (see section 3). Furthermore, optical water quality of rivers is typically highly variable, mainly with flow [*Julian et al.*, 2008b; *Smith et al.*, 1997], so light penetration is also expected to be appreciably variable. Characterizing this variability in terms of a statistical distribution of empirical measurements of light attenuation would be very onerous. Ideally, distributions of light penetration at particular river sites would be constructed from routine optical measurements made as part of river water quality monitoring that covers a wide range of states of flow, for example, the NRWQN in New Zealand [*Smith and Maasdam*, 1994].

[1]National Institute of Water and Atmospheric Research, Hamilton, New Zealand.

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[6] We sought to develop a model for estimating light penetration into rivers using the following more easily measured optical water quality measures: CDOM, the beam attenuation coefficient, and nephelometric turbidity. We took a statistical approach, measuring light penetration at sites in the NRWQN at times of routine water quality sampling, augmented with measurements on optically diverse rivers on the west coast of New Zealand's South Island. Multiple regression was used to develop statistical relationships between light (irradiance) attenuation coefficients and the routinely measured optical variables.

2. Theoretical Background

[7] One of the most important optical properties of a water body is attenuation of sunlight with depth, as characterized by the depth attenuation coefficient (m^{-1}) [*Kirk*, 1994]. "Light" in this context is usually downwelling irradiance, E_d (W m^{-2}), as measured by a sensor with a flat diffuser with its surface level so as to "look" upward in water. The downwelling irradiance attenuation coefficient is defined as

$$K_d = -\frac{1}{E_d}\frac{dE_d}{dz} = -\frac{d(\ln E_d)}{dz}, \qquad (1)$$

where z is depth below the water surface [*Davies-Colley et al.*, 2003]. Attenuation coefficients of identical form and units can be defined for upwelling irradiance as received by an identical irradiance sensor looking downward, scalar irradiance as received by a sensor with a spherical diffuser that is equally sensitive to light from all directions, and radiance as detected by sensors sensitive only to light from a particular direction [*Kirk*, 1994].

[8] These diffuse light attenuation coefficients are referred to as "apparent" optical properties because they depend somewhat on the angular structure of the incident light field [*Kirk*, 1994] in contrast with "inherent" optical properties (IOPs), such as the absorption coefficient, a, and scattering coefficient, b, that depend only on water composition. However, *Baker and Smith* [1979] have shown that K_d (at least for narrow wave bands) is relatively insensitive to solar altitude and other attributes of the light field, so it is convenient to think of a particular water body as being characterized by a particular value of K_d, just as it may be (more rigorously) characterized by a particular value of b and a. For wider wave bands, notably for the whole photosynthetically available radiation (PAR, 400–700 nm) wave band, K_d(PAR) tends to be higher near the water surface than at depth because of spectral "narrowing" as some wavelengths (including red colors absorbed by water itself) are removed from the light field with increasing depth, despite a countervailing tendency for increasing diffusion of the light field to increase K_d(PAR) with depth [*Kirk*, 1985]. However, the change of irradiance attenuation with depth is often small and may be neglected to a first approximation [*Kirk*, 1994].

[9] Both the fundamental (inherent) optical processes of scattering and absorption of light contribute to attenuation of irradiance with depth in waters [*Kirk*, 1985]. However, absorption contributes more strongly because it actually extinguishes light photons whereas scattering merely changes their direction. Scattering contributes to diffuse light attenuation mainly by forcing light photons to take a tortuous path down through the water column thereby increasing their chance of being absorbed over a given depth interval [*Kirk*, 1985]. *Kirk* [1981] has shown that K_d depends linearly on the absorption coefficient and on the square root of the scattering coefficient.

[10] The sum of the light absorption and scattering coefficients is known as the beam attenuation coefficient, $c = a + b$. This quantity (also an IOP) has the same units as irradiance attenuation (m^{-1}) but is a distinct quantity. The light beam attenuation coefficient, c, is only broadly predictive of the diffuse light attenuation coefficient, K_d, because these two distinct attenuation coefficients measure different aspects of water clarity (light penetration versus visual clarity). Indeed, *Preisendorfer* [1958] derived an inequality showing that diffuse light attenuation is bounded in magnitude by the beam attenuation coefficient and light absorption coefficient, a: $c > K_d > a$, so K_d never exceeds c.

[11] Several categories of light-attenuating constituents can be recognized in natural waters [*Davies-Colley et al.*, 2003]. Water molecules absorb red light strongly but other (visible) colors only weakly, while their scattering is very weak and only noticeable in optically pure waters. CDOM (aquatic humus) absorbs light strongly, particularly at the blue end of the visible spectrum, and is sometimes referred to as "yellow substance," recognizing the yellow hue it imparts to water [*Davies-Colley and Vant*, 1987]. CDOM is conveniently indexed by light absorption measurements on filtered water samples in a spectrophotometer at blue or ultraviolet wavelengths [*Kirk*, 1976]. Particulate matter scatters light strongly and may also absorb light and is often indexed by nephelometric turbidity, T_n [*Davies-Colley et al.*, 2003]. Using turbidity as an index inevitably causes some difficulties with interpretation because it "lumps" three distinct categories of particulate matter, differing appreciably in optical properties, that are present in waters. Suspended inorganic particles have a high refractive index relative to water and so scatter light strongly and often dominate turbidity, whereas detrital particulate organic matter tends to have rather similar light-absorbing properties to CDOM as well as scattering light. The third particulate constituent is phytoplankton (conveniently indexed by concentration of the pigment chlorophyll a), which scatters light strongly and absorbs both red and blue light, so imparting a green color to eutrophic waters. Rivers typically have low chlorophyll a concentrations, except where impounded, which simplifies optical water quality and prediction of light penetration compared to standing waters containing appreciable phytoplankton.

3. Methods

3.1. Approach

[12] Our aim was to develop an empirical model relating the irradiance attenuation coefficient, K_d, in rivers, as measured with sensors of PAR [*Kirk*, 1994], to optical water quality variables that are routinely measured as part of water quality monitoring programs. We wish, eventually, to use the extensive 20-year-old databases in New Zealand's NRWQN [*Smith and Maasdam*, 1994] to construct time distributions of lighting in New Zealand rivers over all

c calculated by (2)

Table 1. River Sites at Which PAR Attenuation Coefficients, K_d, Were Related to Optical Water Quality[a]

River Site (Site Code)	Region	Description	Latitude, Longitude	Date	K_d (m^{-1})	y_{BD} (m)	c (m^{-1})	T_n (NTU)	g_{340} (m^{-1})
NRWQN sites									
Motueka at Gorge (NN2)	Nelson, SI		41.633, 172.914	8 Nov 2004	0.27	13.09	0.367	0.24	0.73
Grey at Waipuna (GY3)	west coast, SI		42.354, 171.786	9 Nov 2004	0.41	4.20	1.143	0.39	2.11
Buller at Longford (NN5)	west coast, SI		41.765, 172.387	8 Nov 2004	0.45[b]	5.035	0.95	0.44	1.42
Motueka at Woodstock (NN1)	Nelson, SI		41.249, 172.823	8 Nov 2004	0.56	5.445	0.88	0.37	2.40
Buller at Te Kuha (GY1)	west coast, SI		41.836, 171.678	9 Nov 2004	0.56	2.8	1.71	0.82	2.17
Grey at Dobson (GY2)	west coast, SI		42.452, 171.299	9 Nov 2004	0.65[b]	3.6	1.33	0.75	3.84
Motu at Waitangirua (GS3)	east coast, NI		38.200, 177.621	22 Aug 2006	0.81	1.35	3.56	2.3	3.90
Waipa at Otewa (HM1)	Waikato, NI		38.267, 175.350	19 Aug 2004	1.2	0.96	5.00	3.1	3.79
Ohinemuri at Karangahake (HM6)	Waikato, NI		37.418, 175.718	14 Dec 2005	1.23[b]	1.135	4.23	1.5	8.89
Waihou at Te Aroha (HM5)	Waikato, NI		37.545, 175.708	14 Dec 2005	2.2[b]	0.508	9.45	12	8.83
Waipa at Whatawhata (HM2)	Waikato, NI		37.798, 175.152	19 Aug 2004	2.8	0.26	18.5	10	6.60
Waipaoa at Kanakania (GS1)	east coast, NI		38.468, 177.881	23 Aug 2006	5.28	0.085	56.5	73	3.80
Supplementary sites									
Duffers Creek at SH6	west coast, SI	colored, clear	43.032, 170.655	11 Nov 2004	0.73	3.37	1.42		17.7
Wanganui at SH6	west coast, SI	glacier fed	43.166, 170.627	11 Nov 2004	0.96	0.50	9.60		1.35
Hokitika at Gorge	west coast, SI	glacier fed	42.955, 171.016	10 Nov 2004	1.36[b]	0.343	14.0		1.73
Whataroa at SH6	west coast, SI	glacier fed	43.286, 170.403	11 Nov 2004	2.26	0.20	24.0		1.88
Frosty Creek at SH6	west coast, SI	very colored	42.807, 170.944	10 Nov 2004	3.13	0.47	10.2		62.6

[a]Optical water parameters are visibility, y_{BD}; beam attenuation coefficient, c (estimated from visibility); turbidity, T_n; and CDOM indexed by g_{340}. Twelve National Rivers Water Quality Network (NRWQN) sites, in two regions of North Island (NI) and two regions of South Island (SI), are listed in order of increasing K_d, and data are also given for five supplementary river sites on the South Island's west coast (at which turbidity was not measured). NTU, nephelometric turbidity units.

[b]Irradiance attenuation measured by profiling from a nearby bridge.

states of flow. We therefore measured irradiance attenuation at a diverse selection of NRWQN sites in a brief campaign meshed with routine water quality visits and subsequently used statistical techniques to relate K_d to optical water quality.

[13] The optical variables measured routinely in the NRWQN that are therefore potential explanatory surrogates for irradiance attenuation are CDOM (indexed by absorption of water filtrates at blue or near-UV wavelengths), light scattering by particles (as indexed by turbidity measured by laboratory nephelometer), and visual clarity (measured as the horizontal sighting range of a submerged black disc) [*Davies-Colley*, 1988]. Turbidity, T_n, correlates fairly closely (inversely) with black disc visibility ,y_{BD}, and is far more commonly measured around the world. However, turbidity has some important drawbacks, including that is not a true physical quantity [*Davies-Colley and Smith*, 2001; *Smith et al.*, 1997] such that different nephelometers may give different turbidities on the same water. In contrast, visibility is a "proper" physical quantity from which light beam attenuation, c (an IOP [*Kirk*, 1994] at about 550 nm, the wavelength of peak sensitivity of the human eye), may be estimated from the well-established inverse relation [*Zanevald and Pegau*, 2003]

$$c = \frac{4.8}{y_{BD}}. \quad (2)$$

3.2. Field Sites

[14] Twelve sites in New Zealand's NRWQN were visited once each for measurements of downwelling irradiance attenuation at times of field measurements and water sampling as part of ongoing routine water quality monitoring (Table 1). The sites (locations shown by *Smith et al.* [1997]) were chosen to cover a wide range of optical types of rivers. Additionally, one NRWQN site, the Waihou River at Te Aroha, which is located conveniently close to our Hamilton laboratory, was visited repeatedly (n = 14) at times of routine monthly network sampling visits so as to provide a test data set over a range of different states of flow.

[15] None of these NRWQN sites is dominated, optically, by just one light-attenuating component such as mineral turbidity or CDOM [*Smith et al.*, 1997]. So, in order to widen the statistical "scope" and likely the applicability of empirical models, we sought "end-member" rivers in the west coast region of the South Island which is notable for diversity of river water optics. Large glacier-fed rivers in this region are appreciably turbid ("milky" blue-green in appearance), particularly during spring snowmelt, because of high concentrations of mineral particulates (glacial flour) in otherwise optically almost pure water. In marked contrast, small lowland rivers in the same region are typically visually clear but strongly colored by CDOM (often yellow to orange in hue), reflecting high rainfall leaching of aluminum and iron sesquioxides that would otherwise immobilize humic substances within soils. Accordingly, we augmented the NRWQN data set by visiting the west coast in the southern spring (November) and sampled three large glacier-fed rivers (Hokitika, Wanganui, and Whataroa Rivers) in snowmelt spate, as well as two small visually clear but humic-colored lowland rivers (Table 1). Supporting optical water quality measurements on these "supplementary" sites followed NRWQN protocols (section 3.4).

3.3. Light Penetration Measurements

[16] The irradiance (diffuse light) attenuation coefficient, K_d, is best estimated from a profile of light measurements plotted on a logarithmic scale versus depth below the water surface, z, according to the equation (derived from equation (1))

$$\ln(E_d) = -K_d z + \ln(E_d(0^-)), \quad (3)$$

where $E_d(0^-)$ is the below-surface downwelling irradiance (at infinitesimal depth). However, the profiling method requires ambient lighting to be steady and also requires sufficient depth of water, ideally deeper than the euphotic depth (depth at which irradiance is attenuated to 1% of incident light) in order to recognize trend in K_d with depth. In clearer rivers there is seldom sufficient water depth for profiling to the euphotic depth, even in deep pools. Furthermore, changeable incident light, which is common in New Zealand, with its maritime climate and often cloudy and windy weather, can compromise depth profiles [*Davies-Colley et al.*, 2003]. In changeable ambient light or in optically shallow water the transmission method is a better approach for estimating K_d. A matched pair of irradiance sensors is used to measure the transmission over a known depth interval, according to the equation (also derived from equation (1))

$$K_d = \frac{\ln(E_2/E_1)}{\Delta z}, \tag{4}$$

where E_2/E_1 is the ratio of irradiances at depth z_2 to that at z_1; that is, the irradiance transmittance over depth interval $\Delta z = z_1 - z_2$.

[17] Where a suitable bridge site was located at or close to water quality monitoring sites, measurements were carried out from the bridge deck, either by the transmission method (equation (4)) or (preferably) by profiling (equation (3)). Because bridges are typically located at narrow and deep channel reaches, optical depth of water was often sufficient for profiling (i.e., depth approaching or greater than euphotic depth). For bridge profiling, light measurements were made with a matched pair of Li-Cor LI-192SA sensors of PAR connected to a Li-Cor LI-1000 data logger (LiCor Inc, Lincoln, Nebraska). A bridge-gauging crane fitted with a hydrometric winch with mechanical depth counter was used to profile PAR in the river water under bridges. The gauging wire was held near vertical in the river current, with a 25 kg hydrometric streamlined weight. For transmission measurements, two PAR sensors were mounted at the desired vertical displacement along a custom-made stainless steel frame of 3.8 m length. The bottom of this frame was fixed to the hanger bar of the hydrometric weight and the top was clipped onto the winch wire, so that the sensors had the correct orientation as the array was lowered into the water.

[18] Where no suitable bridge was located, transmission measurements were made (according to equation (4)) by wading using a custom-made frame to hold two matched light sensors level and displaced by a known vertical distance [*Davies-Colley et al.*, 2005]. This frame has an adjustable cradle to hold the data logger above water level and at a convenient height for the operator. A matched pair of Skye SKP215 PAR sensors (Skye Instruments Ltd, Powys, Wales) was deployed on the frame, connected to a Li-Cor LI-1000 data logger.

[19] Transmission measurements (from bridges or by wading) were fairly straightforward under overcast conditions in which incident light is diffuse so that "instantaneous" measurements of PAR transmission were stable and provided a good estimate of K_d(PAR). However, transmission measurements under clear sky in optically shallow river water were highly unstable, owing to refraction of the solar beam through wavelets and turbulent eddies on the river water surface. Data logging for several minutes was required to smooth transmission readings when clear Sun lighting was unavoidable.

[20] We recognize that our river K_d measurements are likely to be slightly biased high, owing to the typical trend for K_d to decrease with depth (approaching a steady minimum at great depth) as the more strongly attenuated wavelengths are progressively removed from the light field [*Kirk*, 1994]. However, given the difficulties with measuring K_d in rivers and considering that "shallow water" light penetration is what is needed for practical applications in these water bodies in any case, we believe our approach is pragmatic.

3.4. Optical Water Quality Measurements

[21] Optical water quality measurements in the NRWQN have been well described in several publications [*Smith and McBride*, 1990; *Smith and Maasdam*, 1994], including reports on optical aspects [*Davies-Colley and Smith*, 2001; *Smith et al.*, 1997], so only a brief overview is given here.

[22] In the field, visual water clarity is measured by the black disc technique [*Davies-Colley*, 1988; *Davies-Colley et al.*, 2003]. A viewer fitted with a 45° mirror is used to observe the visual target (black disc) in the horizontal direction under the water surface with a precision of about ±5%. Water samples obtained on field visits are chilled during overnight air freight to the NIWA Hamilton Laboratory for next-day water quality analyses, including turbidity and CDOM. Turbidity is measured routinely in the NRWQN by a Hach 2100A nephelometer, an instrument that is still considered the defacto standard in water quality work [*Davies-Colley and Smith*, 2001]. CDOM is indexed by light absorption measurements by spectrophotometer on membrane filtrates at 340, 440, and 740 nm, following protocols originally proposed by *Kirk* [1976]. At 740 nm in the near-infrared part of the spectrum, CDOM absorption is very low and almost all of the absorbance measured by spectrophotometer is due to light scattering by filter-passing colloids in the filtrate. This near-infrared absorbance provides a means for correcting absorbance measurements at shorter wavelengths for colloid scattering. Filtrate absorption coefficients (m^{-1}) at 340 nm are calculated as follows (cuvettes of 40 mm = 0.04 m path length are used routinely):

$$g_{340} = \ln(10)\frac{[A_{340} - (740/340)A_{740}]}{0.04}, \tag{5}$$

where A is spectrophotometer absorbance ($\log_{10}$ of transmission) and ln(10) (= 2.303) converts from $\log_{10}$ to natural logarithms. The second term corrects for positive bias from residual scattering, assuming (1) that near-infrared absorbance at 740 nm is entirely due to scattering and (2) scattering varies inversely with wavelength (in accord with empirical investigations). We used g_{340} as a CDOM index rather than g_{440} because of greater precision at the UV wavelength in rivers low in CDOM.

4. Results

[23] The NRWQN sites, listed in Table 1 in order of ascending PAR attenuation coefficient, K_d, separate into a

Table 2. Correlation Matrices for Optical Water Quality Variables[a]

Variable	K_d	c_{550}	T_n	g_{340}
K_d	1	0.94	-	0.52
c_{550}	0.985	1	-	0.28
T_n	0.97	0.98	1	-
g_{340}	0.74	0.71	0.65	1

[a]Data from Table 1. Pearson moment coefficients are given (for log-transformed variables) for NRWQN sites ($n = 12$) below the self-correlation diagonal and for the whole data set ($n = 17$) above this diagonal. Note that turbidity, T_n, was measured only at NRWQN sites.

clear South Island (SI) group followed by a more light-attenuating North Island (NI) group. K_d varied twentyfold overall, from 0.27 m^{-1} in the very clear water of the Motueka at Gorge site (Nelson region, SI) to 5.28 m^{-1} in the very turbid Waipaoa River (east coast, NI), but there was a 150-fold range in beam attenuation and visibility between the same rivers (Table 1).

[24] Table 2 shows correlation matrices for the optical water quality variables. K_d is closely correlated to the beam attenuation coefficient, c_{550}, and to turbidity, T_n (c_{550} and T_n are themselves closely correlated), and less closely correlated to CDOM (g_{340}). Correlation coefficients in Table 2 are higher for the 12 NRWQN sites alone (r values below the self-correlation diagonal) than for all 17 sites (r values above this diagonal), reflecting the optical diversity of the supplementary sites.

[25] Figure 1 shows measured diffuse light attenuation coefficients, K_d, plotted versus beam attenuation coefficients and versus turbidity. (Logarithmic scales are used for optical variables in Figures 2–5 because of the log symmetry of the distributions and because the relationships between the variables are well fitted by power law functions.) Beam attenuation or turbidity alone accounts for much of the variation in light penetration. That is, turbid river waters tend to have high K_d values and correspondingly low light penetration (which is inversely related to K_d). However, despite the close correlation, there is some residual scatter in Figure 1, showing that prediction of light penetration based on beam attenuation or turbidity alone would not be completely satisfactory.

[26] We expected that CDOM, being a strong absorber of light, would also contribute to irradiance attenuation. A plot of diffuse light attenuation coefficients, K_d, versus g_{340} (Figure 2) shows a relatively weak, but definite, correlation (see also Table 2). The supplementary (west coast, SI) river sites add considerable variation and fall into two distinct clusters on either side of the NRWQN sites in Figure 2, with the three large glacier-fed rivers contrasting with the two humic-colored lowland rivers. Identification of individual rivers in Figures 1 and 2 suggests that together beam attenuation (or turbidity) and CDOM may account for most of the overall variation in K_d.

[27] Accordingly, multiple linear regression models were constructed for log-transformed variables (Table 3). Accounting for CDOM increases explanatory power when this constituent varies appreciably (notably among the five supplementary sites in Table 1). Figure 3 shows diffuse light attenuation coefficient, K_d, as predicted by the statistical models plotted against measured values. Both models have excellent explanatory power and can predict K_d with good precision, although a direct comparison of r^2 values is not meaningful because model 2 refers only to NRWQN sites ($n = 12$) that have less CDOM diversity than the five supplementary sites. The precision of model 1 (about ±18%) may be compared with the aggregate error in the component measurements: of order 5% for c_{550} calculated from visibility observations [*Smith*, 2001], 10% for CDOM as g_{340} (R. J. Davies-Colley and J. W. Nagels, unpublished data, 2008), and 10% for K_d (RMS deviation of our replicate measurements). The aggregate (square root of the sum of squares) of these relative errors is about 15%, so clearly, most of the regression error can be attributed to measurement error.

[28] Figure 4 shows predictions of K_d (model 1, Table 3) versus measurements at one NRWQN site (Waihou at Te Aroha) made on 14 occasions of monthly NRWQN sampling visits (which are assumed to be randomly distributed with respect to flow and hence optical water quality). Note that these test data were not used in model development. Most of the data points plot below the 1:1 line, suggesting underprediction of K_d, although two low K_d values (at times

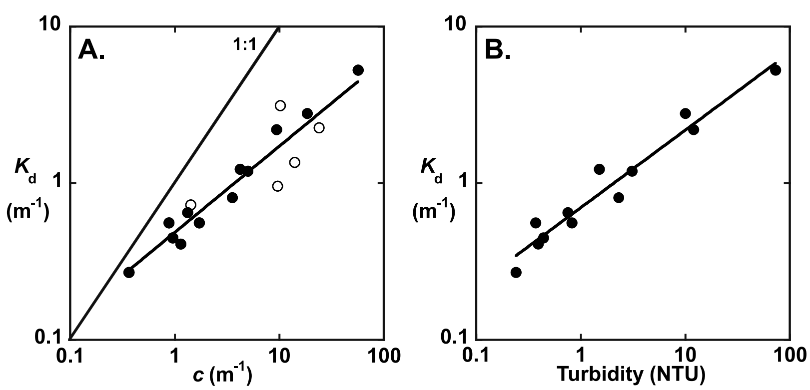

Figure 1. Irradiance attenuation coefficient for PAR plotted versus optical water quality in 17 New Zealand river waters, including 12 National Rivers Water Quality Network (NRWQN) sites (solid circles) and 5 supplementary sites (open circles). (a) K_d versus beam attenuation coefficient, c (r^2 is 0.97 for (log-transformed) data from NRWQN sites and 0.88 for all data). The 1:1 line is shown. (b) K_d versus turbidity, T_n ($r^2 = 0.95$ for NRWQN data).

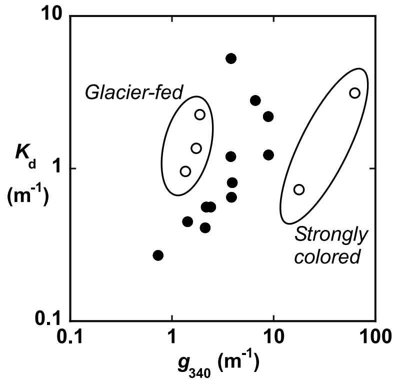

Figure 2. Irradiance attenuation coefficient for PAR versus CDOM (as indexed by g_{340}) in 17 New Zealand river waters. Twelve NRWQN sites are shown with solid circles, and five supplementary sites (open circles) fall into "glacier-fed" and "strongly colored" clusters.

of low flow and clear water) are overpredicted (mean overall relative deviation is −6%). However, the statistical model captures most (85%) of the variation in irradiance attenuation in this river with the expected overall precision (standard error is 15%).

5. Discussion

[29] We have used a special measurement campaign to develop a means for predicting light penetration in rivers from the following (more easily measured) optical water quality variables: beam attenuation coefficient, turbidity, and CDOM. Our simple models should be useful for estimating lighting in rivers where no light penetration data are available but other optical water quality variables have been measured. Furthermore, as we show below, these simple models enable light penetration in rivers to be estimated as a function of flow from optical water quality measurements that themselves may be expressed as functions of flow.

[30] The data set we have used for model development (Table 1) is noteworthy for considerable optical diversity, with visual clarity ranging 150-fold from the very turbid Waipaoa River (visibility of 85 mm) to the very clear Motueka River (visibility of 13 m). The data set also covers a nearly 100-fold range in CDOM with inclusion of a very strongly humic-colored stream among the supplementary sites. Clearer rivers than the Motueka at Gorge site are probably very rare, globally, although clearer standing (fresh) waters occur, notably some unusual lakes and spring waters that approach optically pure (fresh) water, e.g., Waikoropupu Springs [*Davies-Colley and Smith*, 1995]. We would not recommend extrapolating the regression models to attempt estimation of light penetration into clearer river waters than the Motueka, not least because K_d varies appreciably over the PAR band (400–700 nm), so K_d(PAR) is poorly defined in extremely clear waters and decreases with water depth owing to the spectral narrowing phenomenon [*Kirk*, 1994]. Figure 1a also suggests that the equations in Table 3 may not "work" in extremely clear waters. Extrapolation of the regression line in Figure 1a to the left (with decreasing c) causes it to intersect the 1:1 line, but because K_d can never exceed c, the real relationship between these variables is expected to curve asymptotic to the 1:1 line ($K_d = c$) as K_d approaches c in extremely clear waters.

[31] Nephelometric turbidity, which is commonly measured as part of routine river quality monitoring, provides a useful means for estimating light penetration in rivers. The empirical equation we obtained for K_d as a function of T_n and CDOM is similar in form to that reported previously for gold mine–impacted (and strongly humic-colored) streams on the South Island's west coast [*Davies-Colley et al.*, 1992]. The finding in the present study of coefficients of about 0.5 for both (log-transformed) turbidity (an index of light scattering) and beam attenuation (typically due mostly to light scattering) is consistent with modeling work by *Kirk* [1981], who found that irradiance attenuation follows a square root function of the scattering coefficient.

[32] Although turbidity data are potentially very useful for estimating river light penetration, we caution against uncritical application of relationships between K_d and T_n. Different nephelometers give different numerical readings in nephelometric turbidity units on the same water sample owing to differences in optical design [*Davies-Colley and Smith*, 2001], so no "universal" relationship can be expected. Thus, model 2 (Table 3) may give biased estimates if applied to turbidity monitoring data from a different nephelometer than the Hach 2100A. Therefore, local calibration of K_d to the particular nephelometer used in a river water quality monitoring campaign would be necessary for accurate estimation of light penetration.

[33] In contrast to turbidity, beam attenuation is a proper scientific quantity (and an inherent optical property), so the function of beam attenuation we report here (model 1) may reasonably be expected to be universally valid in rivers throughout the world. Beam attenuation is usually measured (most commonly in situ) with a beam transmissometer [e.g., *Gallegos*, 2005], a type of instrument increasingly used in research programs where the optics of the water body is of particular interest but less often in routine water quality monitoring and rarely in rivers. Beam attenuation can also be measured in the laboratory by a (suitably modified) spectrophotometer [e.g., *Julian et al.*, 2008a]. The black disc visibility measurement, because it yields a precise (±5%) estimate of beam attenuation weighted to the sensi-

Table 3. Multiple Linear Regression Models of Irradiance Attenuation in New Zealand Rivers[a]

Model	Equation	n	r^2	s
1a	$\log_{10}(K_d) = -0.4079 + 0.5034 \log_{10}(c_{550}) + 0.2145 \log_{10}(g_{340})$	17	0.95	0.079
1b	$\log_{10}(K_d) = -0.0649 - 0.5034 \log_{10}(y_{BD}) + 0.2145 \log_{10}(g_{340})$	17	0.95	0.079
2	$\log_{10}(K_d) = -0.2564 + 0.4313 \log_{10}(T_n) + 0.2300 \log_{10}(g_{340})$	12	0.96	0.074

[a]Model 1 is a function of ($\log_{10}$ transformed) beam attenuation coefficient, c_{550}, or, equivalently, visibility, y_{BD}, and CDOM indexed by g_{340}; model 2 is a function of turbidity, T_n, and CDOM. Coefficients of determination, r^2, values and standard errors of the regressions, s, are given. Note that the coefficients are identical for models 1a and 1b, with the exception of the constant term, because beam attenuation was estimated from visibility by equation (2).

c=4.8/y_BD, but this does not give me 13 m for Motueka (c=0.88), while it does give me 85 mm for Waipaoa (c=56.5), so I think 13 m should be 5.4 m.

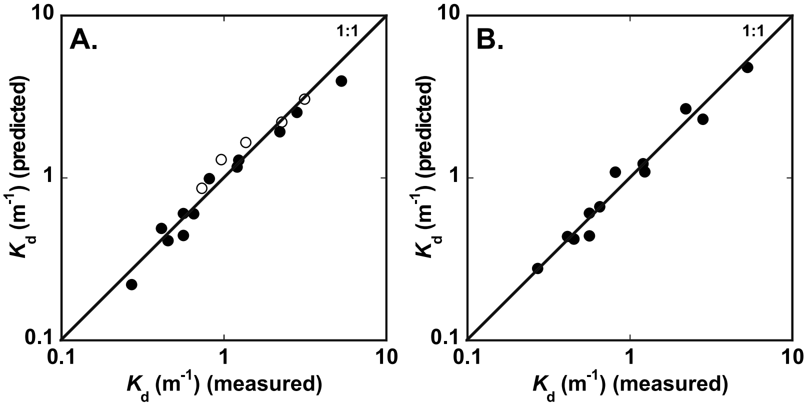

Figure 3. K_d as predicted from the statistical models (Table 3) compared with measured K_d in 17 New Zealand rivers. (a) Predictions from model 1 (Table 3) and (b) predictions from model 2 (Table 3). Twelve NRWQN sites are shown as solid circles, and five supplementary sites are shown as open circles.

tivity of the human eye (equation (2)) and, therefore, may be itself considered an IOP [*Zanevald and Pegau*, 2003], is a valuable optical variable that deserves to be more widely adopted in general water quality work [*Davies-Colley and Smith*, 2001]. We have shown in this study that visibility measurement in rivers, as well as directly characterizing visual clarity, permits useful estimation of light climate as a function of flow.

[34] The irradiance attenuation coefficient in waters is sometimes confused with the beam attenuation coefficient since both variables may be taken as quantifying water clarity and both have the same units of m^{-1} [*Davies-Colley and Smith*, 2001]. However, these quantities, measuring light penetration and visual clarity, respectively, should be carefully distinguished. In Figure 1a, all data points plot well below the 1:1 line (mean ± standard deviation of K_d/c = 0.31 ± 0.2), showing that K_d is typically much lower than c in magnitude, and there is considerable scatter about the line of best fit, showing that the two variables are only roughly (and nonlinearly) related.

[35] Numerous studies have sought relationships between light penetration into standing waters and visibility (usually measured as Secchi depth, z_{SD}, observed with a white or black-and-white disc in the vertical direction) [*Davies-Colley and Vant*, 1988]. However, as we have seen, visual clarity alone is not a fully satisfactory estimator of light penetration because of the different optical basis of these quantities. The question arises: Can other supplementary information (besides CDOM) enable light penetration to be estimated from visibility? In lakes the product $K_d z_{SD}$ (where z_{SD} is Secchi depth) has been shown to be a systematic function of reflectance (the ratio of upwelling to downwelling irradiance) [*Davies-Colley and Vant*, 1988] and also of the ratio T_n/CDOM (which itself is correlated to reflectance) [*Koenings and Edmundson*, 1991]. This suggests that K_d might similarly be estimated from visibility in rivers if reflectance were measured as well. However, reflectance is even more difficult to measure than K_d in rivers (because of light reflection off the bottom), so its inclusion in statistical models of K_d, although potentially very helpful in lakes, is probably not practical for rivers.

[36] The fairly accurate prediction of K_d in the Waihou River at Te Aroha (Figure 4) suggests that the models presented here can be relied upon to predict light penetration in rivers over a wide range of flow states. Use of model 1 with long-term data sets in the NRWQN (which covers a very wide range of flow states, having been running monthly since 1989) permits estimation of K_d as a function of the time distribution of optical water quality, which, in turn, is (mainly) a function of flow [*Smith et al.*, 1997]. Figure 5 gives such distributions for K_d in the Waihou River and also for the (very clear) Motueka River at Gorge and (strongly light-attenuating) Waiapoa River at Kanakanaia (sites visited in this study). An alternative (and almost equivalent) means for calculating such distribution curves would combine flow distribution curves with power law functions relating optical water quality to flow [*Smith et al.*, 1997] and the models we present here for estimating K_d from optical water quality.

[37] Figure 5 also shows the distribution curve of median irradiance attenuation coefficients for sites in the NRWQN. This distribution curve was compiled from the distribution of median values for y_{BD} and g_{340} reported by *Smith et al.* [1997] used in the empirical model for light attenuation presented here (model 1b). Median K_d values for 64 (unimpounded) NRWQN river sites range from 0.30 m^{-1} in the Motueka River, the clearest river site in the NRWQ,

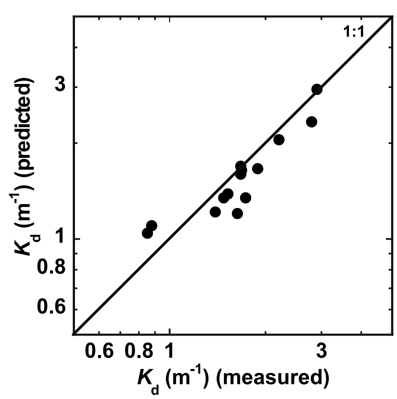

Figure 4. K_d as predicted from statistical model 1 (Table 3) compared with measured K_d at one river site (Waihou at Te Aroha) on 14 occasions of routine NRWQN sampling.

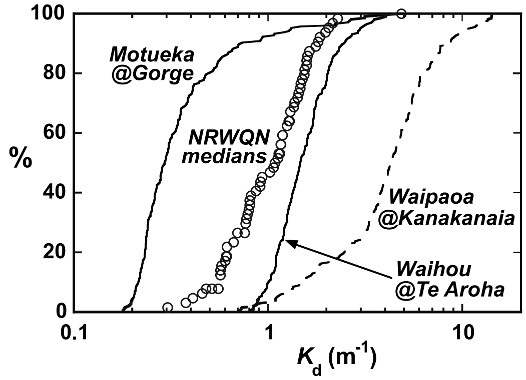

Figure 5. Distribution of K_d at three NRWQN sites, Motueka at Gorge, Waihou at Te Aroha, and Waipaoa at Kanakanaia. Also shown is the distribution of median K_d values for 64 unimpounded rivers in the NRWQN from optical water quality medians summarized by *Smith et al.* [1997].

to 4.8 m^{-1} in the Waipaoa River, the most turbid river, a (sixteenfold) range that although wide, is not nearly as wide as the (143-fold) range in median visibility at the same sites [*Smith et al.*, 1997]. The distribution of K_d medians, which has an overall median of 1.08 m^{-1}, gives an indication of the overall distribution of light penetration into New Zealand river waters and is expected to be valuable for putting measurements or modeling of a particular river in context as regards light attenuation. For example, Figure 5 suggests that the Waihou at Te Aroha is a fairly typical New Zealand river as regards light attenuation.

[38] Recently, *Julian et al.* [2008b] reported a framework (the benthic light availability model (BLAM)) for predicting irradiance at the bed of rivers that accounts, sequentially, for shading by topographic features (hills and riverbanks) and riparian vegetation, surface reflection, and penetration of light to the river bed (which is controlled by water depth as well as the irradiance attenuation coefficient). Since both water depth and irradiance attenuation increase with river flow, benthic lighting varies strongly with flow and, therefore, with time, at least in comparatively deep and light-attenuating (i.e., optically deep) rivers. BLAM, as presented by *Julian et al.* [2008b], uses turbidity (alone) to estimate K_d, but we have shown that CDOM, as well as particles, attenuates light and is ideally accounted for. The models of K_d reported here could be used to improve estimation of light attenuation in river waters within the BLAM framework by combining CDOM data with turbidity or beam attenuation data. Such a framework should be very valuable for predicting, for different purposes, the time dependence of lighting at the bed or averaged over the water column or the spatial dependence of lighting in rivers as a function of channel morphology.

[39] To conclude, light penetration in rivers, as quantified by the irradiance attenuation coefficient for PAR, can be fairly accurately (±18%) estimated from beam attenuation or turbidity measurements combined with CDOM measurements by using simple empirical models developed from a campaign of field measurements on New Zealand rivers. Such models may be used to construct distributions of light penetration in rivers wherein optical characteristics typically vary strongly with flow. We suggest that these equations predicting light penetration as a function of more easily measured optical water quality variables will be widely useful for estimating lighting in rivers.

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R. J. Davies-Colley and J. W. Nagels, National Institute of Water and Atmospheric Research, P.O. Box 1115, Hamilton, New Zealand. (r.davies-colley@niwa.co.nz)