Disentangling effects of eutrophication and CDOM on visual water clarity in Lake Brunner: preliminary data and methods

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1. Executive summary

Secchi depth has declined in Lake Brunner since the 1990s as the chlorophyll *a* concentration, a proxy for algal biomass, has increased. This report presents preliminary information on the visual range and underwater light penetration in Lake Brunner, and contributes toward disentangling the various effects on water clarity.

Lake Brunner is a humic stained lake with a relatively high absorption by coloured dissolved organic matter (CDOM). As a result attenuation of light as it passes from the surface downwards is relatively high (K_d (PAR) = 0.53 m^{-1}). Secchi depth is lower than would be expected from algal biomass concentrations alone because CDOM absorption reduces visibility in the vertical direction.

A significant inverse relationship between Secchi depth and chlorophyll *a* concentration suggests that changes in water clarity mostly result from changes in algal biomass on a seasonal basis. However, a decreasing interannual trend in Secchi depth since the 1990s may be in part a result of changes in concentrations of CDOM. In addition, light availability in Lake Brunner may at times be more limiting for algal growth than the availability of nutrients.

A theoretical basis is provided with analytical tools for a monitoring program aimed at furthering the understanding of water clarity in Lake Brunner. A number of recommendations are given for a more detailed study to examine the effects of various factors on visual clarity and light penetration in Lake Brunner.

2. Introduction

Managing declining water quality in Lake Brunner is WCRC's primary water quality issue. Declining clarity is a key indicator and concern. While increased phytoplankton (driven by phosphorus) has driven declining clarity in the last 15 years, natural coloured dissolved organic matter (CDOM) may have contributed to clarity reduction. Comparatively little is known about the dynamics of CDOM in New Zealand lakes. Better understanding of mechanisms influencing clarity in Lake Brunner and of how we factor CDOM into evaluating clarity trends will help WCRC manage the catchment more effectively.

Lake water clarity is related to trophic state, and measuring the maximum depth at which a Secchi disk is visible (Secchi depth) is the most popular method for monitoring lake clarity. In recent years Secchi depth has declined in Lake Brunner (Verburg 2009), and chlorophyll *a* concentrations have increased, suggesting a causative link between trophic state and visual clarity. Secchi depth has been used as a target for water quality management in many lakes. However, Secchi depth is reduced not only by the abundance of phytoplankton but also by dissolved organic matter which may be derived from the catchment. While the abundance of phytoplankton is directly related to the trophic state of the lake, the concentration of dissolved organic matter is typically only weakly, if at all, related to the trophic state. In particular, coloured dissolved organic matter (CDOM) is typically derived from the catchments of humic stained lakes. Increasing CDOM concentrations can result in lower algal abundance and productivity than predicted based on nutrient concentrations, by decreasing the light available for algal growth. As a result the question whether water quality declines when Secchi depth decreases is confounded by CDOM, a factor that may or may not be unrelated to anthropogenic activity and that is generally unrelated to trophic state. Lake Brunner, in common with most lowland water bodies in the West Coast Region, has fairly high CDOM concentrations (Paerl et al. 1979; Gallegos et al. 2008), probably reflecting soil leaching in the per-humid climate with leaching of Fe and Al from catchment soils which would otherwise sorb and immobilize humics (Gallegos et al. 2008). It is therefore important to be able to distinguish between the different influences that together determine water clarity in Lake Brunner.

3. Methods

In order to provide a national-scale reference for Lake Brunner, data for chlorophyll *a* concentrations and Secchi disk depths for 2005 to 2009 were used for all lakes that are monitored by Regional Councils in New Zealand (Verburg et al. 2010). Means and medians for each lake were calculated for chlorophyll *a* concentrations (n = 113) and Secchi depth (n = 70).

Maps and other background information on Lake Brunner are given in Verburg (2009). Historical data for light absorption observed at 340 and 440 nm (an index of coloured dissolved organic matter, CDOM), and data for chlorophyll *a*, Secchi depth, turbidity and total suspended solids in Lake Brunner were supplied by Jonny Horrox (West Coast Regional Council).

For indexing CDOM, 10 cm cells were used to measure absorbances (A340 and A440, $\log_{10}$ of transmission) of dissolved matter in a spectrophotometer on filtered (0.45 µm membrane filter) water samples until the end of 2005, and 4 cm cells since 2006. To calculate the absorption coefficients g340 and g440 (normalized for cell path, i.e., in m^{-1} units), absorbance is divided by cell length. For instance,

$$g340 = \frac{\ln(10)A340 - (740/340)A740}{y} \qquad \text{Eq. 1}$$

which includes a correction for bias from residual scattering derived from near-infrared absorbance at 740 nm (Davies Colley and Nagels 2008), and with y = cell length (in metres). The factor ln 10 (= 2.303) converts from log-base 10 units (of absorbance) to natural logarithms.

The absorption coefficient g360 was estimated as

$$g360 = \frac{g340}{e^{S(360nm-340nm)}} \qquad \text{Eq. 2}$$

following Davies-Colley and Vant (1987), with the exponential spectral slope coefficient S = 0.0187 nm^{-1}, resulting in

$$g360 = \frac{g340}{1.454} \qquad \text{Eq. 3}$$

The concentration of dissolved organic carbon (DOC, in g m^{-3}) was estimated as

$$DOC = 1.9 + \frac{0.596g360}{\ln(10)} \qquad \text{Eq. 4}$$

following the empirical equation relating DOC to absorption at 360 nm in West Coast waters given by Collier (1987).

The light attenuation with depth (K_d, for downward irradiance) of photosynthetically active radiation (PAR, unit: µmol s^{-1} m^{-2}) was determined on 30 November 2010 in the center of the lake (n = 2), and in Iveagh Bay (n = 1) and Cashmere Bay (n = 1), with two cosine quantum

PAR sensors (LiCor LI-192SB) deployed jointly on a frame spaced apart by a 2.72 m depth increment. The distance from the top of the frame to the top sensor was measured with a tape measure and the depth from the water surface to the frame controlled with a rope divided into 1 m graduations. The depth of the top of the frame was recorded during each irradiance measurement at 1 m depth intervals and exact depths of both sensors calculated afterwards. The day of the field visit was very calm and sunny with occasional clouds obscuring the sun. Underwater irradiance measurements were taken near midday and Secchi depth was determined at each site simultaneously. Irradiance was recorded as a running average of the past 20 seconds with this averaging period starting after the sensors had been lowered to a particular depth, except for the first of the two irradiance profiles at the central lake site. During the latter measurement only instantaneous values of irradiance were recorded.

The attenuation of downwelling irradiance (K_d) was calculated as the slope (absolute) of the regression of ln-transformed irradiance versus depth, for both sensors. In addition, K_d was estimated at 1 m intervals as

$$K_d = -\frac{\ln(\frac{I_1}{I_2})}{z_1 - z_2} \qquad \text{Eq. 5}$$

following Davies-Colley et al. (1984), with I_1 and I_2 the light intensity at the deeper sensor and the shallower sensor respectively, and z_1- z_2 the distance between the sensors (2.72 m). The values of K_d calculated at each 1 m interval were averaged to give a third value of K_d for each light profile.

4. Results and Discussion

4.1 Optical properties

The behaviour of light under water or water clarity has two main aspects: (1) the visual clarity measured by the distance over which an observer at the surface can see objects under water (for instance Secchi depth = SD) and (2) light penetration measured by the rate of decline of irradiance as light travels from the surface downwards (K_d, in m^{-1}). The former aspect is important for organisms that need to see objects under water such as aquatic consumers that are searching for food, and also for human swimmers, while the second aspect is important for phytoplankton and other aquatic plants which need light to grow. These two measures of water clarity are governed by key properties of light under water, the beam attenuation coefficient c, the (total) absorption coefficient a, and the scattering coefficient b. The scattering and absorption coefficients are additive: $c = a + b$. The scattering coefficient b is only weakly dependent on the wave length of light, whereas a varies markedly with wavelength (Kirk 1994a). Absorption by dissolved material (primarily CDOM) is readily measured with a spectrophotometer on filtered water samples while b is very difficult to measure and is usually estimated, indirectly, by difference: $b = c - a$ (Kirk 1994a; but see Kirk 1994b). The beam attenuation coefficient c is best measured with a beam transmittance meter but is more easily derived from various relationships with SD and the black disk visibility (BD).

4.2 Lake water quality trends

Since the early 1990s Secchi depth in Lake Brunner declined as chlorophyll *a* concentrations increased (Fig. 1), suggesting increased phytoplankton productivity. Increasing algal productivity in the lake was apparently driven by increasing concentrations of phosphorus and nitrogen (Verburg 2009). The chlorophyll *a* concentration increased significantly with total phosphorus (TP; $p < 0.005$, $n = 71$, $r = 0.36$) and with decreasing Secchi disk depth (SD; $p < 0.0001$, $n = 62$, $r = 0.49$), but not with total nitrogen (TN; $p > 0.05$, $n = 65$), which is consistent with phosphorus limitation of algal growth in lake Brunner (Verburg 2009). Similarly, SD decreased significantly with increasing TP ($p < 0.01$, $n = 65$, $r = 0.37$) but not with TN ($p > 0.05$, $n = 57$).

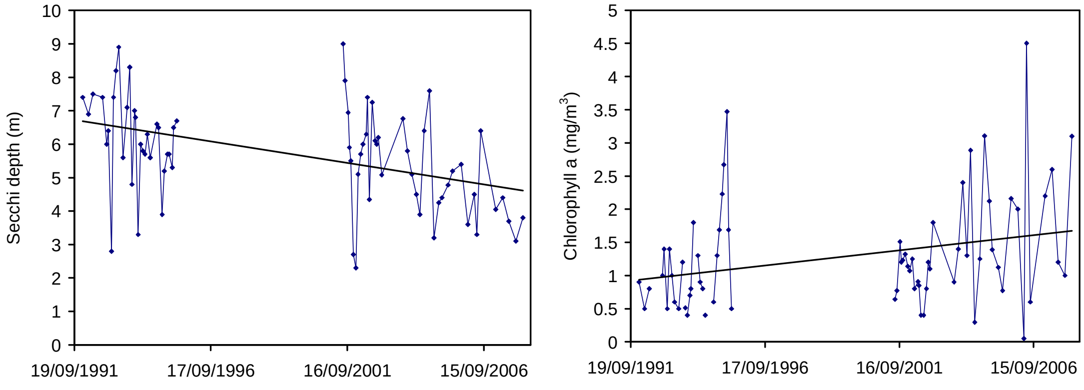

Figure 1. Time trends in Lake Brunner of Secchi depth and the concentration of chlorophyll *a*. From Verburg (2009).

Turbidity is the relative tendency of water to scatter light and is related to particles in the water. There was no significant trend since 2003 in turbidity (mean 0.88 NTU; Fig. 2) or in the concentration of total suspended solids (TSS, mean 0.97 g m^{-3}; Fig. 3), both factors that affect visual clarity. Absorption coefficients g340 (and therefore estimated DOC) and g440 (Figs. 4 and 5) increased significantly since 2003 ($p < 0.05$ and $p < 0.005$ respectively). An increase in DOC (Fig. 6) is also suggested by comparison with the lower concentration (2.5 g m^{-3}) found in the 1970s (Paerl et al. 1979) and the range found since 2003 (2.8 to 3.2 g m^{-3}). The difference with the (single) value from the 1970s may, however, be explained by the different methods used by Paerl et al. (1979) which included acidification and analysis by a conductometric method after photo-oxidation in the presence of persulphate (Paerl et al. 1979). Absorption coefficients g340 and g440 did not correlate significantly with SD ($p > 0.05$, $n = 24$). Nevertheless, the absence of a correlation of absorption and estimated DOC concentrations with SD is not sufficient evidence that the decrease in SD since the 1990s was entirely driven by an increase in algal biomass (Fig. 1) and not in CDOM. Absorbance data are only available since 2003 and do not span the same period as for which chlorophyll *a* concentration and SD data are available. While the decrease in SD since the 1990s was significant ($p < 0.005$, $n = 68$, $r = 0.37$), there was no trend in SD from 2003 ($p > 0.05$, $n = 28$) and the correlation of SD with TP since 2003 was not significant ($p > 0.05$, $n = 27$). However, the correlation between chlorophyll *a* concentration and SD was significant from 2003, ($p < 0.01$, $n = 28$, $r = 0.60$), suggesting that seasonal changes in water clarity were mostly driven by algal biomass.

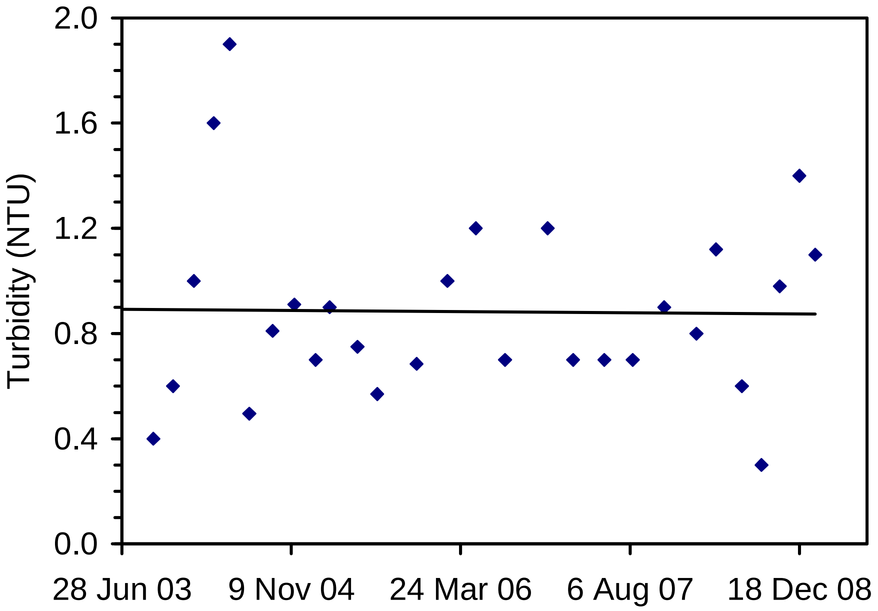

Figure 2. Turbidity in Lake Brunner.

On the other hand, at times low water clarity as a result of the high concentration of CDOM may limit algal productivity and the concentration of algal biomass in Lake Brunner. This would be expected particularly in winter when deep mixing introduces nutrients from the hypolimnion into the epilimnion without resulting in an increase in algal biomass (Verburg 2009). Light limitation of the algal cells, which because of the vigorous mixing find themselves much of the time at depths where they do not receive sufficient light for net

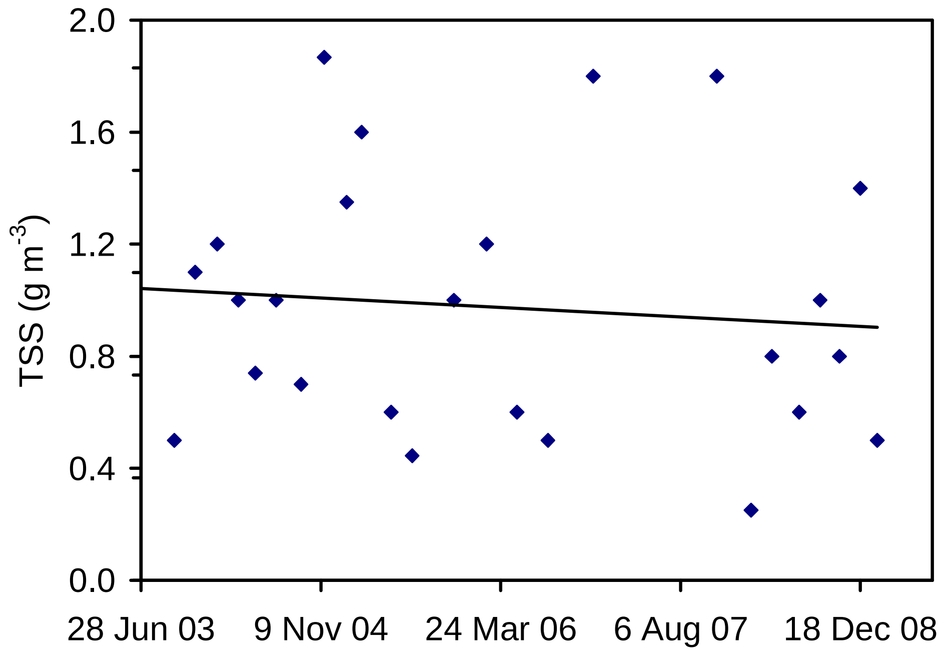

Figure 3. Total suspended solids (TSS).

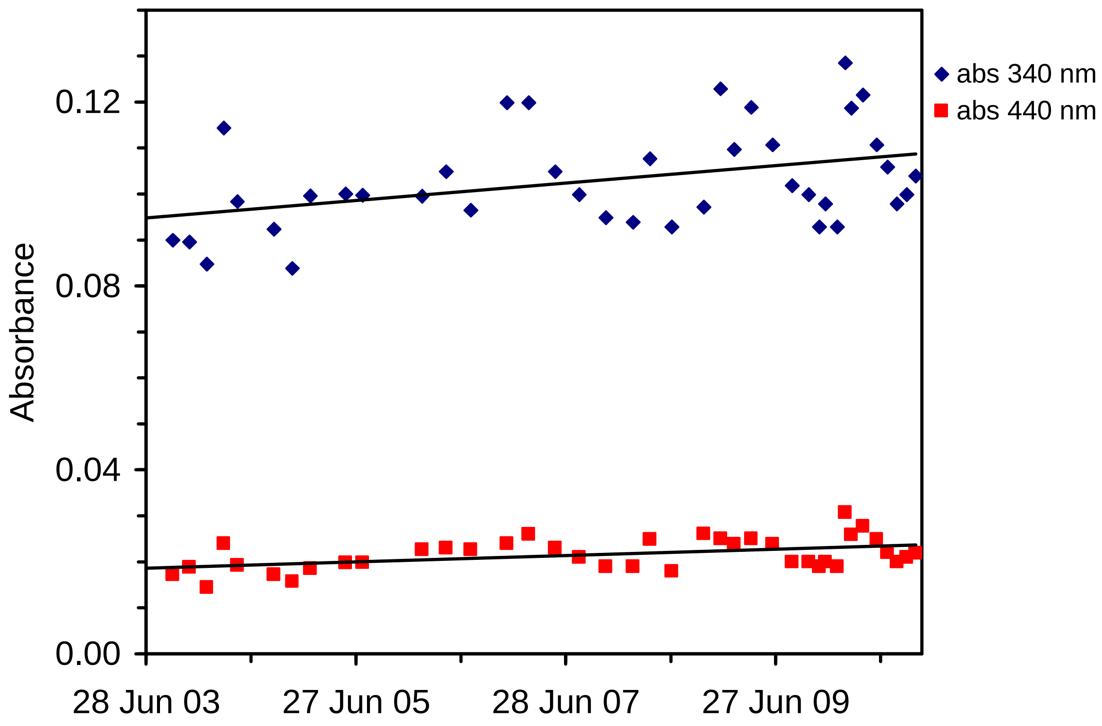

Figure 4. Absorbance at 340 and 440 nm (converted for 4 cm cell size).

photosynthesis, might be responsible for the absence of a growth response to increased nutrient concentrations in winter. It has recently been recognized that in oligotrophic lakes light instead of nutrients may often limit photosynthesis (Karlsson et al. 2009; Cole 2009). Lake Brunner is oligotrophic and is indeed a good example of such a lake.

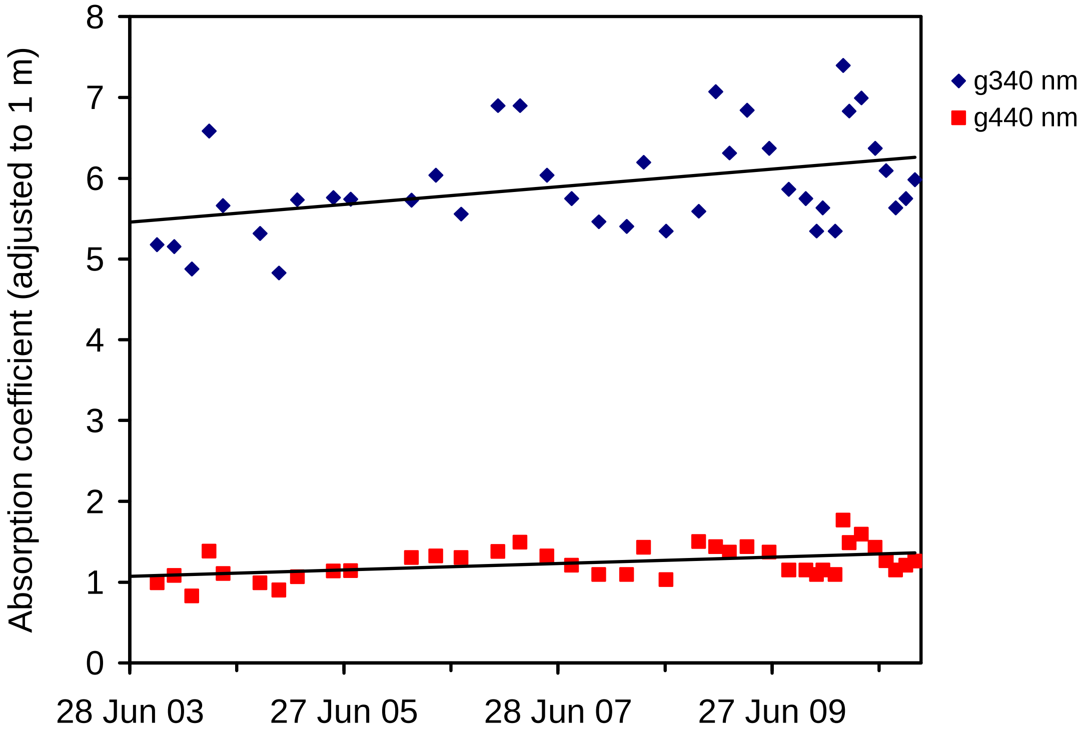

Figure 5. Absorption coefficients at 340 and 440 nm.

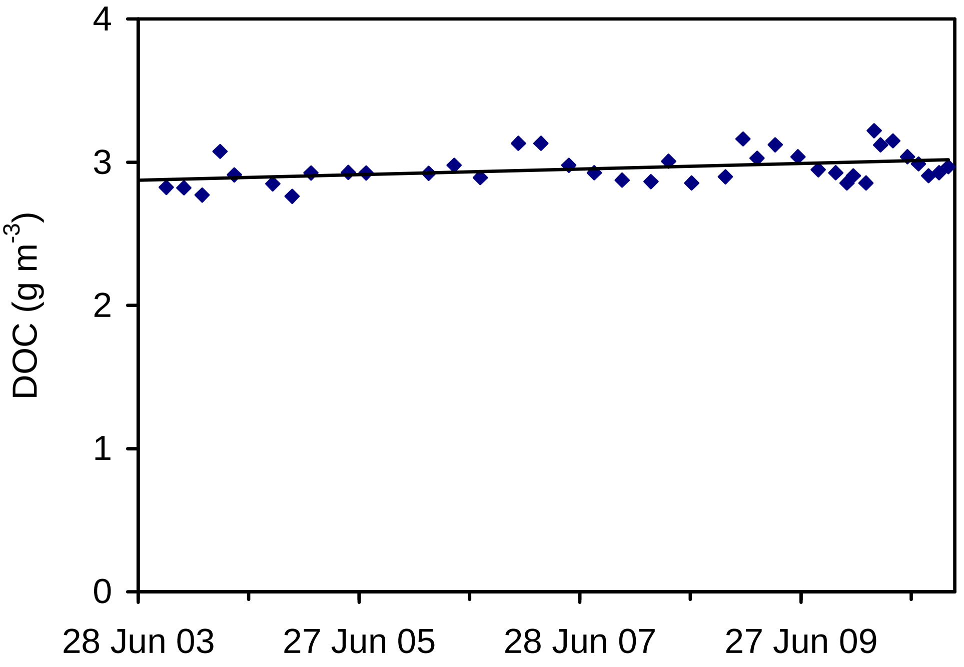

Figure 6. The concentration of dissolved organic matter (DOC) as derived from the measurement of absorption.

The relationship between DOC and absorbance (Eq. 4) was derived by Collier (1987) from stream waters with a large range in concentrations of DOC (0 to 40 g m^{-3}). In the case of Lake Brunner, where DOC is roughly 3 g m^{-3}, the accuracy of the equation of Collier (1987) is probably low, because the equation is not sufficiently sensitive to indicate differences within a small range. In fact, because the intercept of the equation is high (1.9 g m^{-3}), the equation suggests a minimum content of DOC of 1.9 g m^{-3} even when absorbance is zero (the high intercept may be a result of un-coloured (non-absorbing) DOC, i.e. organic carbon that does not contribute to CDOM).

4.3 Relationships between chlorophyll a and Secchi depth

In Lake Brunner SD (2005-2009 mean = 5.20 m) is lower than predicted by a regression on chlorophyll *a* concentrations in lakes that are monitored in New Zealand (Fig. 7; data from Verburg et al. 2010). This suggests that additional factors may affect SD in Lake Brunner, such as the concentration of CDOM which is relatively high in Lake Brunner (Paerl et al. 1979). In Lake Brunner the mean g440 = 1.24 m^{-1}, while the median g440 is about 0.84 m^{-1} in New Zealand rivers (Davies-Colley et al. 2003). On average g440 is probably lower in New Zealand lakes than in the rivers, due to photo-bleaching.

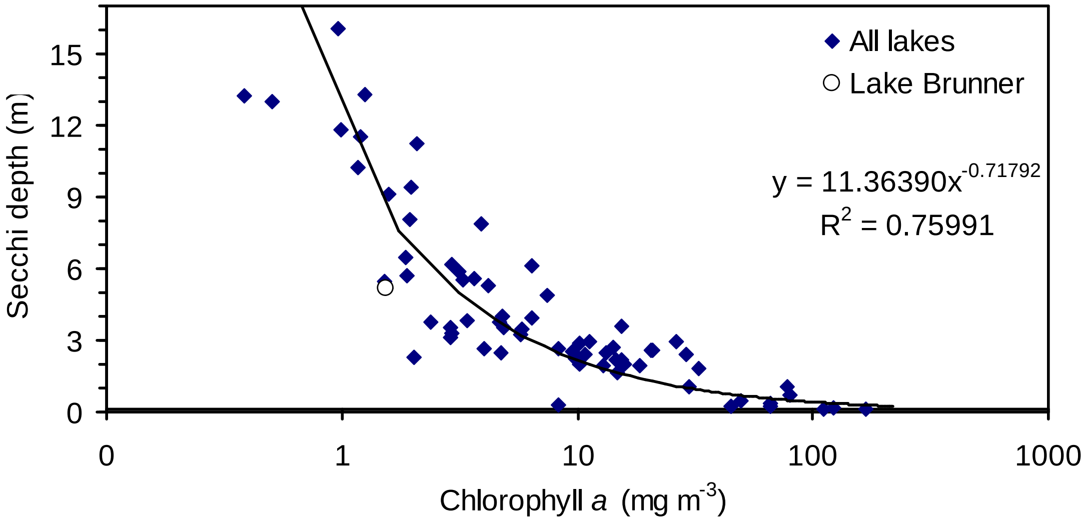

Figure 7. Mean SD plotted against mean chlorophyll *a* concentrations in 70 lakes in New Zealand, with Lake Brunner shown separately. The regression is for all lakes, Lake Brunner included. A linear relationship of chlorophyll *a* with SD^{-1}, a transformation that is often applied to SD data, did not improve the correlation.

Portielje and van der Molen (1999) found that the maximum summer SD for a particular chlorophyll *a* concentration (chlα) in 231 lakes and ponds in the Netherlands is given by:

$$\frac{1}{SD\max} = 0.16 + 0.010chl\alpha \qquad \text{Eq. 6}$$

which in Lake Brunner for the mean chlorophyll *a* concentration of 1.54 mg m^{-3} would suggest a Secchi depth of 5.7 m. However, the relationship for New Zealand lakes between SD and chlorophyll *a* ($y = 11.364x^{-0.7179}$; Fig. 7) suggests that for a chlorophyll *a*

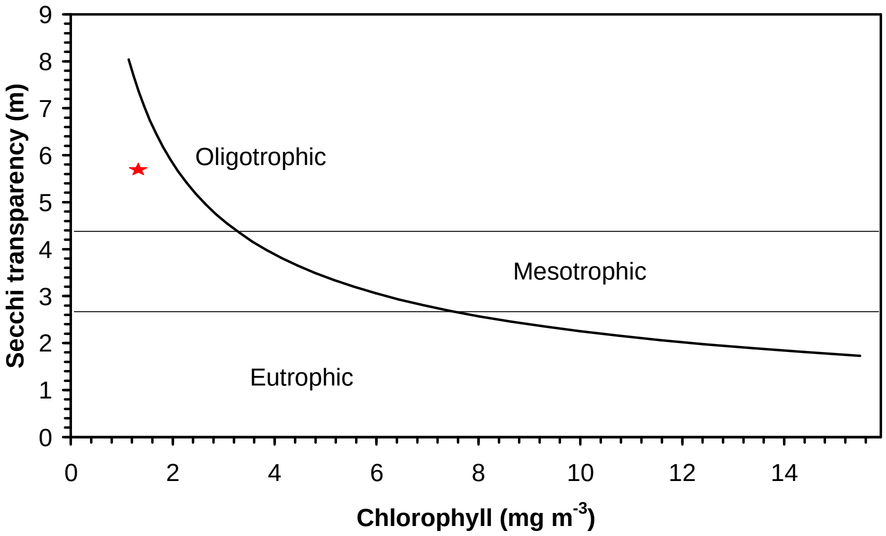

Figure 8. Predicted relationship between chlorophyll *a* and Secchi depth, as estimated by Oglesby and Schaffner (1978). Lines separating trophic status are based on the relationship with total phosphorus concentrations in lakes and the red star is at the position of the 1992-2008 mean chlorophyll *a* concentration and the 1992-2008 mean Secchi depth. From Verburg (2009).

concentration of 1.54 mg m^{-3} in Lake Brunner an average SD of 8.32 m is expected. In addition, a relationship between Secchi depth and chlorophyll *a* concentration, $\log SD = 0.961 - 0.606 \log Chl\alpha$, given by Oglesby and Schaffner (1978) suggests a Secchi depth of 7.04 m in Lake Brunner (Fig. 8). The relation of Oglesby and Schaffner (1978) is expected to hold especially well at the low end of the range of TP concentrations for which the relation was derived (7 to 40 mg m^{-3} TP). However, the relation overestimates Secchi depth in Lake Brunner from the chlorophyll *a* concentration, by almost 2 m (Verburg et al. 2009). The mean SD in Lake Brunner in 2005-2009 was 5.20 m (Verburg et al. 2010). The discrepancy may be explained by non-algal turbidity (Lind 1986) – which seems unlikely in Lake Brunner since there is little soil erosion in the catchment, or by CDOM – which is high in many Westland water bodies, although Lake Brunner is less stained than other beech forest lakes (Paerl et al. 1979).

4.4 Downwelling attenuation

The average attenuation of downwelling light K_d was 0.53 m^{-1} in the center lake site and in Iveagh Bay (Tables 1-5; Figs. 9-11). Correlations for the regression of ln irradiance against depth were good (mean r = 0.99). The energy flux of PAR expressed in μmol s^{-1} m^{-2} can be converted to W m^{-2} as 1 μmol s^{-1} m^{-2} = 0.217 W m^{-2} (6.02 x 10^{17} quanta per μmol and 2.77 x 10^{18} quanta per watt, Kirk 1994a) and was ~ 200 W m^{-2} near the surface. However, this is an approximate estimate and may differ by 10 to 20% because of the shift in wave length with depth. There was no appreciable difference between the irradiance profiles and values of K_d computed using a 20 second running average of irradiance and the first irradiance profile at the center of the lake site for which only instantaneous values of irradiance were recorded. K_d values computed from the ratios of irradiance measured simultaneously by the two sensors (Eq. 5) instead of from the slope of the profiles were quite variable, with outliers (lower panels in Figs. 9-12).

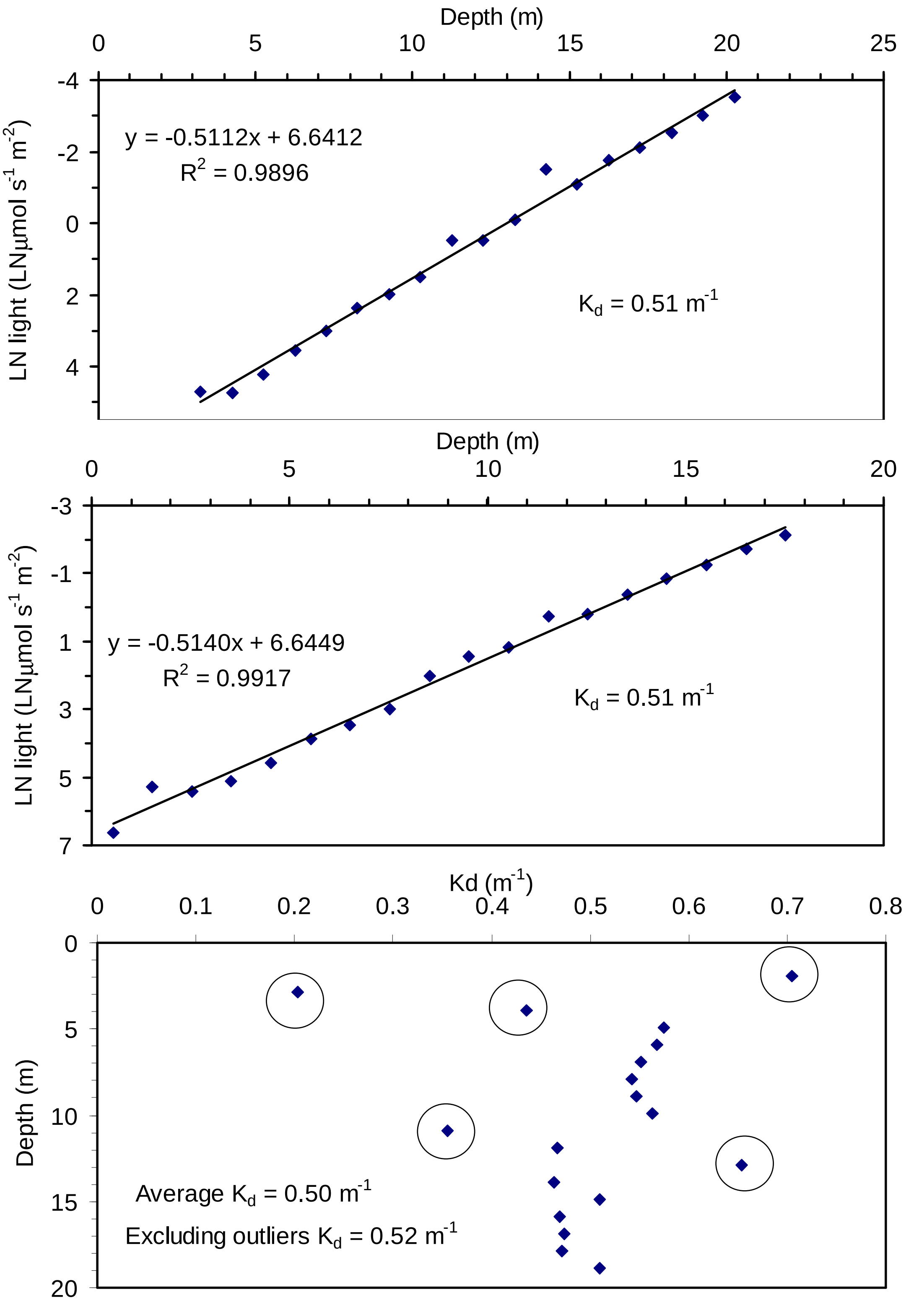

Figure 9. The natural logarithm of irradiance plotted against depth for 2 sensors 2.72 m apart in depth, with estimates of K_d. Center lake site, first measurement series, with irradiance recorded as instantaneous values. Bottom panel: K_d between the sensor depths calculated at 1 m intervals, plotted against the mean depth of the two sensors. Potential outliers are indicated by circles.

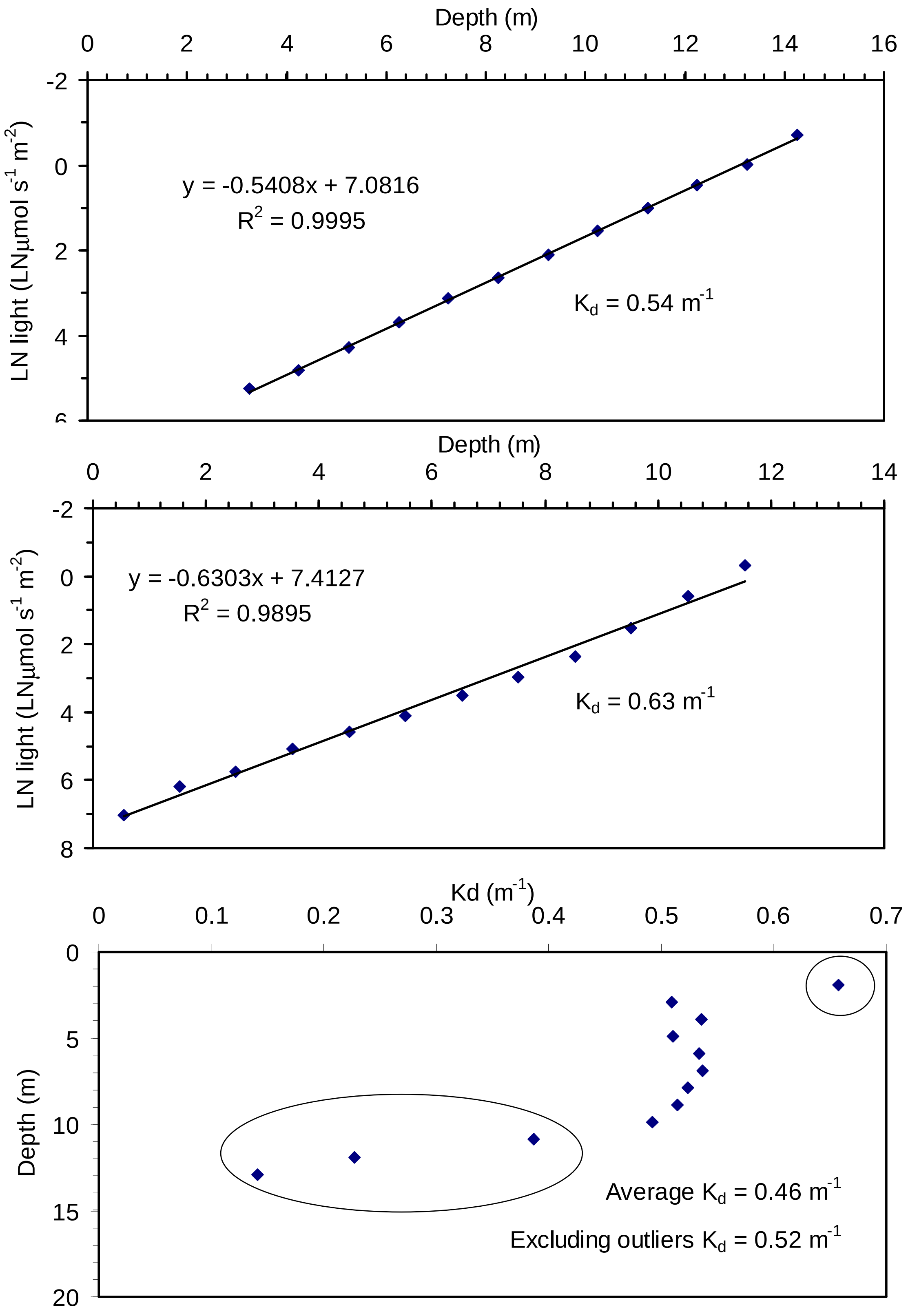

Figure 10. The natural logarithm of irradiance plotted against depth for 2 sensors 2.72 m apart in depth, with estimates of K_d. Center lake site, second measurement series, with irradiance recorded as 20 second averages. Bottom panel: K_d between the sensor depths calculated at 1 m intervals, plotted against the mean depth of the two sensors. Potential outliers are indicated by circles.

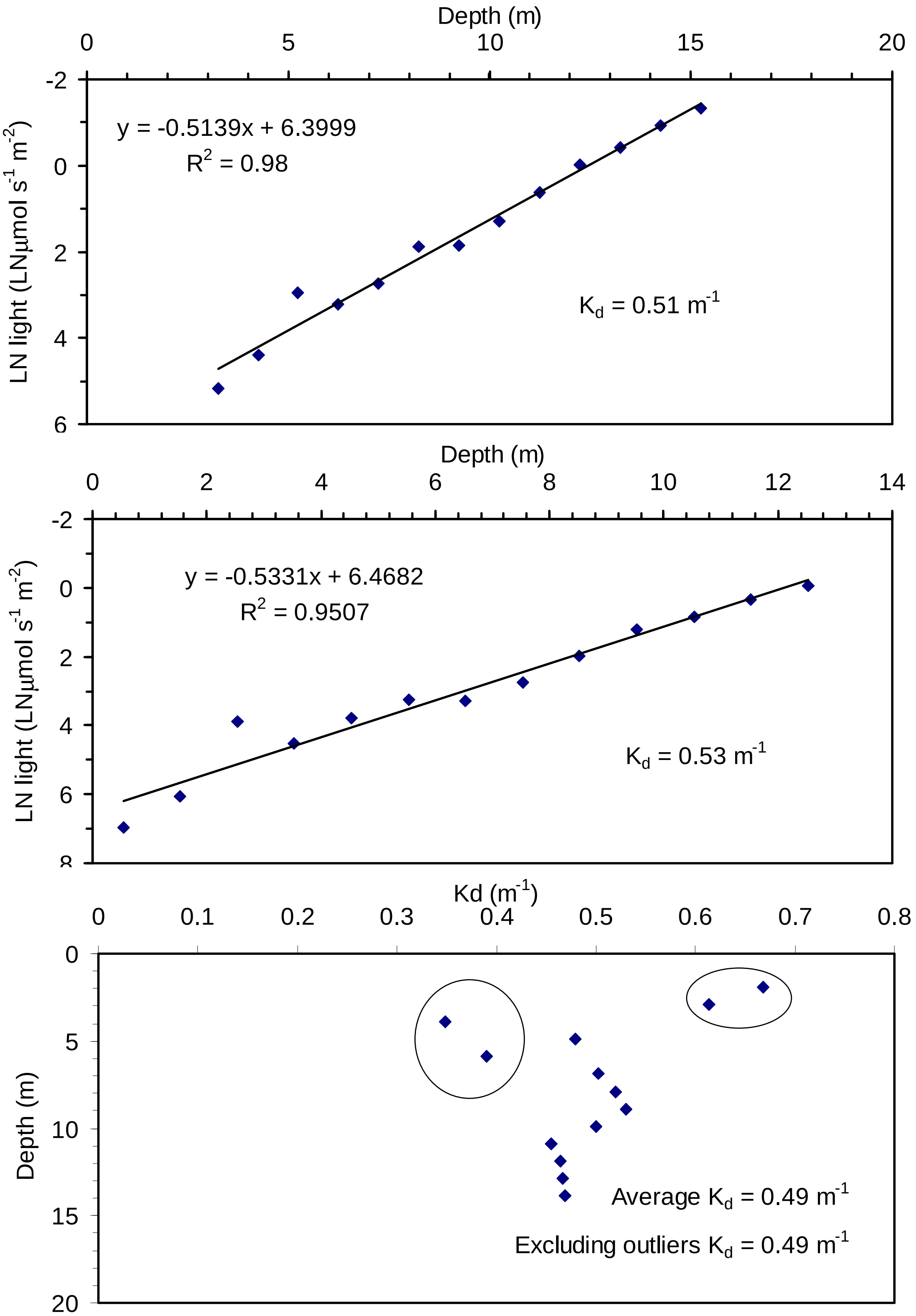

Figure 11. The natural logarithm of irradiance plotted against depth for 2 sensors 2.72 m apart in depth, with estimates of K_d. Iveagh Bay, with irradiance recorded as 20 second averages. Bottom panel: K_d between the sensor depths calculated at 1 m intervals, plotted against the mean depth of the two sensors. Potential outliers are indicated by circles.

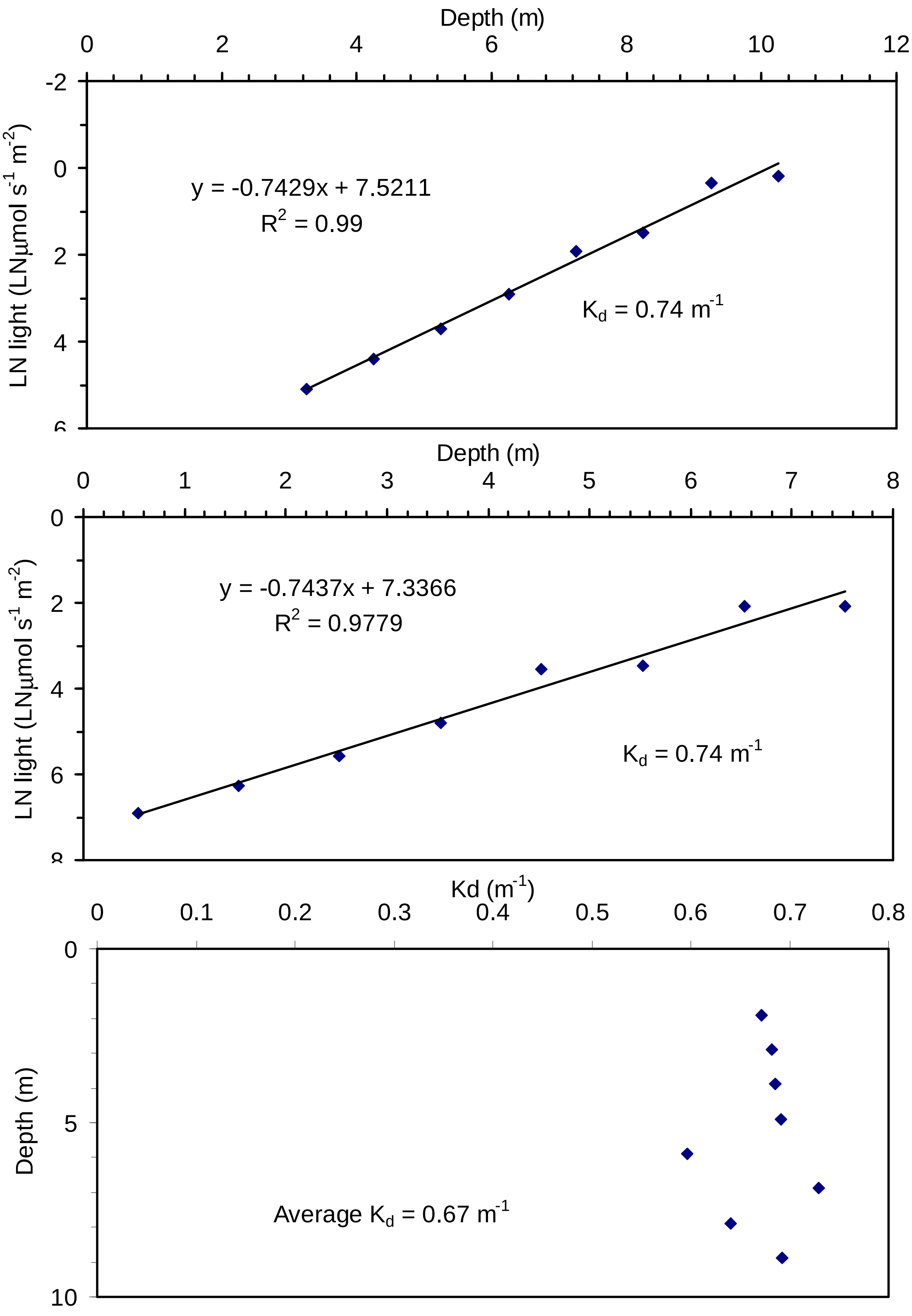

Figure 12. The natural logarithm of irradiance plotted against depth for 2 sensors 2.72 m apart in depth, with estimates of K_d. Cashmere Bay, with irradiance recorded as 20 second averages. Bottom panel: K_d between the sensor depths calculated at 1 m intervals, plotted against the mean depth of the two sensors.

There was some indication of a shift in K_d to lower values below 10 m depth in the center lake and in Iveagh Bay (Figs. 9-11). Some change in K_d with depth is expected with usually somewhat elevated K_d in the near surface layer because of the rapid absorption of wavelengths in the red range of the visible spectrum (Kirk 1994a; see also Gallegos et al. 2008 for spectral optical properties in Lake Brunner). However, such a change in K_d with depth would be expected to occur only in the upper few meters.

Clarity was substantially lower in Cashmere Bay than in the center of the lake, with an average $K_d = 0.72$ m^{-1} and a Secchi depth of 4.18 m. On average 28% of the light at the upper sensor was received at the lower sensor in the center lake and Iveagh Bay sites (standard deviation 10%, n = 43) but less at Cashmere Bay because light penetration was less there while the distance between the sensors was the same as at the other sites (mean 16%, standard deviation 2%, n = 8).

The euphotic zone (Z_{eu}), defined as the depth at which light levels are 1% of light at the surface, can be estimated from K_d as

$$Z_{eu} = \frac{\ln(100)}{K_d} \qquad \text{Eq. 7}$$

A K_d of 0.53 m^{-1} implies a Z_{eu} of 8.7 m. Z_{eu} is generally expected to be more or less the maximum depth at which net photosynthesis by phytoplankton is possible. Z_{eu} is on average roughly 2.5 times the Secchi depth in lakes but the ratio Z_{eu}/SD is appreciably lower in Lake Brunner because of the effect of strongly absorbing CDOM which results in relatively high K_d.

4.5 Relationship between downwelling attenuation and Secchi depth

On average in natural waters that are not heavily humic stained or turbid a relationship between attenuation and Secchi depth (SD) is expected according to

$$K_d = \frac{k}{SD} \qquad \text{Eq. 8}$$

with k ~ 1.7 (Graham 1966; Davies-Colley et al. 2003). The mean of $k = K_d$*SD in 28 lakes in New Zealand, calculated from data of K_d and SD given in Davies-Colley and Vant (1988), was 1.61 (with 95% confidence limits of 0.18), not significantly different from the often used mean value of 1.7. The lakes in the data set of Davies-Colley and Vant (1988) include lakes with a very large range of K_d*SD (varying from 0.59 to 2.82), representing most of the variability among all lakes. Holmes (1970) gives another relationship for Secchi depth and vertical attenuation: $K_d = 1.44$/SD. This equation would suggest a $K_d = 0.27$ m^{-1} when SD = 5.25 m as it was recorded in the center of Lake Brunner in this study. However this relation was inferred from data of turbid waters only. In addition, in the summary of conclusions Holmes wrote that K_d = (1.13/Secchi)+0.10 fitted the data “even better”. This equation would result in $K_d = 0.32$ m^{-1} when Secchi depth is 5.25 m, identical to the result of equation 8 with k = 1.7.

However, the relationship in equation 8, i.e., the value of k, varies with turbidity and with colour (Davies-Colley and Vant 1988; Koenings and Edmundson 1991; Kalff 2003). In contrast to the value of K_d predicted by equation 8 with k = 1.7 from SD = 5.25 m, the mean value of K_d found in the center of the lake was substantially higher, by about 65%. The average of all K_d estimates at the center lake and Iveagh Bay sites was 0.53 m^{-1} (n = 9, Table 5; see Figs. 9-11). The average K_d at the center lake was 0.54 m^{-1} and in Iveagh Bay 0.51 m^{-1}, while Secchi depth was similar in the latter (5.30 m) to that in the center of the lake (Table 5). Equation 8 would suggest a K_d = 0.41 m^{-1} for Cashmere Bay, so also at this inshore site is the observed K_d higher than the predicted K_d, by about 75%. The difference of the average observed K_d with the value expected from equation 8 is explained by the high concentration of dissolved organic matter in the water of Lake Brunner. The presence of dissolved organic matter in the water affects K_d more than Secchi depth. While SD is affected by scattering of light by particles, K_d is much more strongly dependent on absorption than on scattering of light (MfE 1994). Colored dissolved organic matter (CDOM) absorbs rather than scatters light, and therefore the effect of CDOM on light penetration (e.g., K_d and euphotic depth) is much stronger than on visual clarity as measured by Secchi depth. However, particulate scattering, probably mostly by phytoplankton biomass, is likely the main influence on visual clarity in Lake Brunner including on the long term declining trend. Changes in Secchi disk visibility are related more to changes in scattering properties of the water than to changes in attenuation of downwelling surface irradiance (Holmes 1970; Hecky and Fee 1981).

Visual clarity as given by Secchi depth is an index of visual water clarity and records how deep people can see in a lake. In contrast, the penetration of light in the water column determines the depth to which phytoplankton and aquatic plants can grow, i.e., receive sufficient light for net photosynthesis. These two aspects of water clarity, visual clarity and light penetration, are only weakly correlated (Davies-Colley et al. 2003; MfE 1994). Secchi depth is more closely related to the beam attenuation coefficient c than to K_d (MfE 1994). Therefore there is no reason to expect a simple relationship between SD and K_d. In reality K_d*SD (= k) varies mainly with reflectance R, which is given by the ratio of upwelling and downwelling irradiance (Davies-Colley and Vant 1988) and with the ratio b/a.

The dimensionless product K_d*SD has been found to vary from 0.5 to 4.1 in 35 studies summarized by Koenings and Edmundson (1991), and varies with the reflectance R and with the ratio b/a (Davies-Colley and Vant 1988). As a result the usefulness of SD or K_d as an index of trophic state is limited. Instead, K_d*SD has been suggested to be useful as an indicator of change in concentrations of particulates or in CDOM (Koenings and Edmundson 1991). K_d*SD was 2.7 in the center lake site of Lake Brunner, and slightly higher at inshore sites Iveagh Bay (2.8) and Cashmere Bay (3.0). K_d*SD = 2.7-3.0 puts lake Brunner in the range of humic stained lakes (Kalff 2003; Koenings and Edmundson 1991).

K_d*SD is high in humic stained lakes where reflectance in low, low in turbid lakes where reflectance is high, and intermediate in clear lakes (Davies-Colley and Vant 1988; Koenings and Edmundson 1991). For k = K_d*SD in equation 8 a value of 1.7 would only be more or less appropriate for clear lakes and not for a humic stained lake with low reflectance such as Lake Brunner. This conclusion is underlined by the substantially lower Secchi disk depth than predicted from the trend among lakes in general from the relationship with chlorophyll *a* concentration (Figs. 7 and 8).

Davies-Colley and Nagels (2008) derived three multiple linear regression relationships that predict log(K_d) in 17 optically diverse rivers, from log(c_{550}) and log(g_{340}), from log(BD) and log(g_{340}), and from log(turbidity) and log(g_{340}), each with strong correlations (about 0.97).

4.6 Relationship between visual clarity and beam attenuation

As mentioned, SD depends not only on K_d but also on c. Holmes (1970) and Tyler (1968) give the following equation:

$$SD = \frac{\Gamma}{c + K_d} \qquad \text{Eq. 9}$$

Holmes (1970) found the average Γ = 8.9 and Tyler (1968) found the average Γ = 8.69. Vant and Davies-Colley (1984) found a similar value, Γ = 8.25, while Davies-Colley (1984) reported Γ = 9.52. Preisendorfer (1986) determined theoretically that Γ should be roughly between 8 and 9, depending on the threshold contrast of the disk and the reflectance of the disk.

The beam attenuation c can be roughly (Kirk 1994a) estimated from SD by

$$c_{555nm} = \frac{6.4}{SD} \qquad \text{Eq. 10}$$

allowing, if necessary, to estimate K_d from equation 9. Equation 10 predicts c measured at 555 nm wavelength, the wavelength of light for which the human eye is most sensitive (MfE 1994).

A similar relationship as between SD, c and K_d given by equation 9 has been determined between (vertical) black disk visibility (BD) and $c + K_d$:

$$BD = \frac{\Psi_1}{c_{555nm} + K_d} \qquad \text{Eq. 11}$$

Unlike Γ, Ψ_1 does not depend on optical properties of the water or on the ambient light field (Davies-Colley 1988). Ψ_1 is, theoretically, an 'exact' constant (= 4.8; Davies-Colley 1988). Therefore, BD provides a better estimate of c than SD (using either Eq. 9 or Eq. 10). In addition, for horizontal sighting, when the value of K_d is irrelevant because of the angle of observation, the black disk visibility yields the following relationship (Eq.12) (Davies-Colley 1988)

$$BD = \frac{\Psi_2}{c_{555nm}} \qquad \text{Eq. 12}$$

which means that a direct estimate of *c* (at 555 nm) can be obtained from a measurement of the maximum range of the black disk visibility. Davies-Colley (1988) gives $\Psi_2 = 4.8$:

$$c_{555nm} = \frac{4.8}{BD} \qquad \text{Eq. 13}$$

4.7 Reflectance

The quantum irradiance reflectance coefficient R (or simply ‘reflectance’) is given by

$$R = \frac{I_{up}}{I_{down}} \qquad \text{Eq. 14}$$

(Davies-Colley et al. 1988). The reflectance coefficient can be measured directly as the ratio of upwelling irradiance (I_{up}) and downwelling irradiance (I_{down}) with both sensors mounted on the same support, one facing downwards and the other facing upwards respectively (Davies-Colley et al. 1984). The upper faces of both sensors should be at equal depths for the measurement of R. R will change somewhat with depth but will generally approach an asymptotic value at a sufficient depth, where attenuation of upwelling irradiance (K_u) approaches that attenuation of downwelling irradiance (K_d; Davies-Colley et al. 1988).

Reflectance measured at the surface (R_o) is related to the ratio of scattering and absorption:

$$R_o = 0.0063\frac{b}{a} \qquad \text{Eq. 15}$$

(MfE 1994) and can therefore be used to derive the scattering coefficient *b* from *a* and R_o. However, it is difficult to measure R at the surface precisely. In addition, R_o when estimated using PAR is limited in its usefulness for determining *b* because *a* is dependent on wavelength.

The product K_d*SD varies with both R and the ratio *b*/*a*, with increasing values for decreasing R and decreasing *b*/*a* (Davies-Colley and Vant 1988). Reflectance is low in humic stained lakes such as Lake Brunner because absorption is relatively stronger compared with scattering in humic stained lakes. Koenings and Edmundson (1991) found that R explains 72% of the variation in K_d*SD in lakes in New Zealand, the US and Australia, and the overall relation ship ($P < 0.0001$) between R (in %) and K_d*SD was

$$K_d \times SD = 2.49 - 1.24LOG(R) \qquad \text{Eq. 16}$$

This equation predicts R = 0.4 to 0.7% for the range of K_d*SD found in this study (3.0 to 2.7 respectively). In contrast, a plot of K_d*SD versus R in Davies-Colley and Vant (1988) suggests a value of around 2% for R in Lake Brunner. Equation 16 of Koenings and Edmundson (1991) probably does not perform well at the lower end of the range of R and the higher end of the range of K_d*SD, as it likely underestimates R in Lake Brunner.

In 28 lakes in New Zealand K_d*SD (calculated from data of K_d and SD in Davies-Colley and Vant 1988) explains 65% of the variation in R in log-log space (while ignoring differences in angles of incident sunlight, as was done by Koenings and Edmundson 1991):

$$LOG(R) = 1.142 - 1.936 LOG(K_d \times SD) \qquad \text{Eq.17}$$

This relationship predicts R = 1.65 to 2.03% for the range of K_d*SD found in this study in Lake Brunner. These values are larger than predicted by equation 16 (Koenings and Edmundson 1991). However, in this equation the variation at the low end of the scale of R is huge, as with the Koenings and Edmundson (1991) equation (Eq. 16), and neither equation 16 nor equation 17 should be used to estimate R in Lake Brunner.

Davies-Colley and Vant (1988) give an equation that relates SD to *c*, K_d and R:

$$SD = \frac{\ln\left(\frac{0.82 - R}{0.0066R}\right)}{c_{555nm} + K_d} \qquad \text{Eq. 18}$$

R = 2.02% if $\Gamma = 8.69$ (Tyler 1968). This value of R agrees well with R expected in Lake Brunner from a plot versus K_d*SD given by (Davies-Colley and Vant 1988) and the values of K_d*SD determined in this study (between 2.7 and 3.0). However, R in equation 18 is not constant and equation 18 suggests that Γ may vary with R. Equation 18 suggests that if Γ in equation 9, equivalent to the enumerator in equation 18, ranges from 8 to 9 (Preisendorfer 1986), then it follows that R in equation 18 ranges only between 1.51 and 3.97%. This range excludes much of the values of R expected in clear lakes (median R = 5%) and in turbid lakes (median R = 34%; Koenings and Edmundson 1991). The predicted range in R would be 0.56 to 9.95% if Γ in equation 9 ranges from 7 to 10, which would still exclude the turbid lakes. It suggests that the realistic range of Γ among lakes from turbid to humic stained is at least larger than 8 to 9, suggests that Γ cannot be assumed constant, and suggests that equation 9 is not ideal to produce an estimate of *c* from SD and K_d. Instead, if R, SD and K_d are measured, equation 18 allows estimation of c_{555nm}, unless a black disk apparatus is available and equation 13 can be used to estimate c_{555nm}.

4.8 Estimation of *a*, b, and c.

Methods in Kirk (1994b) allow estimation of *a* and of *b* from measurements of K_d and R, and from μ_o, the angle of light underwater. μ_o can be estimated from solar altitude which can be calculated from information of latitude, time of day and day of the year. The angle of the light beam to the vertical plane changes when it passes across the air-water interface due to refraction, by a factor of 0.75 (Snells Law; Kirk 1994a). The vertical attenuation coefficients for both upward and downward irradiance are needed to apply this method. The beam attenuation coefficient *c* can be estimated from SD (Eq. 18) or BD (Eq. 11 or Eq. 12), and the scattering coefficient *b* can be estimated as *b* = *c* – *a*, to compare with the result following Kirk (1994b). Alternatively, *b* can be calculated from reflectance at the surface and *a* (Eq. 15), and *c* = *a* + *b*, however the measured R_o may be unreliable because it is difficult to measure precisely. The amount of temporal variation in *c* that is explained by variation in chlorophyll *a* can be compared with the amount of variation explained by inorganic suspensoids (Vant and Davies-Colley 1986) or by CDOM, or by the product K_d*SD. Multiple regression relationships between a, b and K_d and between a, b and SD may be determined. It must be noted, however, that seasonal changes in water clarity across one year may have different drivers than the inter-annual trend.

Single profile measurements in Lake Brunner given by Gallegos et al. (2008) show that roughly $a_{440nm} = 1.25\ m^{-1}$ for total absorption which requires a scattering correction, as opposed to only absorption by dissolved matter in filtered samples. However, it is similar to the results presented here for absorption by dissolved matter (Fig. 4). Measured at 555 nm the single profile measurements given by Gallegos et al. (2008) show that roughly $a_{555nm} = 0.3\ m^{-1}$ (total absorption), and $b_{555nm} = 0.7\ m^{-1}$, from which it follows that $c_{555nm} = 1.0\ m^{-1}$. Therefore, b:a is roughly 2.3, which agrees with the relation between b:a and K_d*SD given by Davies-Colley and Vant (1988) and our values for K_d*SD for Lake Brunner.

5. Recommendations

Brunner is a (slightly) unusual lake as regards its relatively high CDOM and dark colour (low reflectance). These features may well affect its response to anthropogenic changes in its catchment, including nutrient enrichment. Therefore we recommend on-going study aimed at unravelling the complex interrelationships between CDOM, visual clarity, phytoplankton, and response to nutrients – initially in a (12 month) Envirolink MAG which would focus on in-lake studies of lake optics and light-attenuating materials. The routine monitoring of Lake Brunner (central site) for nutrients, Chl-*a*, Secchi depth and CDOM, would be augmented by measurement of black disc (horizontal) visibility and PAR profiling (up- as well as down-welling PAR) to better characterize the lake optics (in terms of the fundamental inherent optical properties *a*, *b* and *c*) and to permit construction of models (statistical and or optical-mechanistic) for predicting lake response to catchment management (nutrient enrichment or other changes).

The study briefly outlined above is expected to yield some recommendations for ongoing monitoring of Brunner, but some practical points can be mentioned now:

1. Measure SD on sunny side of the boat, and ensure the line is vertical (implies use of a streamlined weight in the presence of windage).

2. Measure (horizontal) BD as well as SD.

3. Measure light (PAR) profiles and R routinely at the central site.

4. Monitor two further sites routinely (Iveagh Bay, Cashmere Bay).

Detailed practical monitoring issues

(1) If measurements at the two light sensors at different depths on the instrument frame are not taken truly simultaneously then there is probably no benefit in using equation 5 at each depth interval, compared with simply regressing all values in a light intensity profile on depth (as in Figs. 9-12, upper 2 panels in each figure). The light intensity data are highly variable and can differ strongly from one second to the next, even when they are a running average of for instance the past 20 seconds. Therefore, instead of writing the data of each sensor at the two depth levels to a notepad (as was done in this preliminary study), to estimate Kd properly at each depth interval it is required to log the light intensity data of both sensors simultaneously to the memory of the LICOR data logger, and to download the results at some later stage after the light profile has been completed.

(2) As a metric to be used as a target for water quality management, we recommend that the trophic level index (TLI) is preferable to Secchi depth. The TLI is a compound metric which is determined from more or less equal weights given to total phosphorus, total nitrogen and chlorophyll a concentrations (Burns et al. 2000). It has been used in the past also to include Secchi depth as a component (Burns et al. 1999; Sorrell 2006), however, a disadvantage of including Secchi depth is that its relationship with trophic state in lakes can be affected by factors which have no bearing on trophic state. This is the case for instance in lakes with high seasonal loads of glacial flour and in lakes with high concentrations of humic acids. In a recent report of water quality in all monitored

lakes in New Zealand Secchi depth was not used as a component of TLI (Verburg et al. 2010).

(3) Secchi disk measurements should always be made on the sunny side of the boat (Tyler 1968; MfE 1994), so that neither the disk nor the water through which the disk is viewed is in the boat shadow.

(4) The suspending rope for Secchi depth must be vertical, because not only will the depth of the disk be less than that indicated by the length of the rope, but in addition, the angle of observation when different from 90 degrees to the surface will diminish the visibility of the disk (Tyler 1968).

(5) If a black disk apparatus is available, it would be an excellent tool to include in the monitoring of the light field in Lake Brunner. This instrument can give more useful data than a Secchi disk, because a black disk reflects no light and therefore its visibility depends only on the optics of the water and not on the nature of the subsurface lighting as with the partially white Secchi disk (Davies-Colley 1988; MfE 1994). The sighting range for a black disk depends only on the attenuation coefficients for the water and not on the ambient light field or reflectance coefficient (Davies-Colley 1988). Estimation of c from black disk visibility is more accurate than from Secchi disk visibility (Davies-Colley 1988). The reflectance of the Secchi disk is assumed to be 0.82 (Tyler 1968) but this is generally not measured and will vary somewhat between disks. For instance, Holmes (1970) found the reflectance of the Secchi disk to be 0.93. Differences in reflectance of the Secchi disk would affect the relationship between SD and c.

(6) Measure reflectance R which is given by Eq. 14. R can then be related to the product Kd*SD as it depends on R (Davies-Colley and Vant 1988). Measurement of R as well as Kd allows estimation of a and b (following Kirk 1994b). The upper faces of both sensors measuring upwelling and downwelling irradiance should be at equal depths for the measurement of R.

(7) Measure absorbance at 555 nm which is the wavelength of highest sensitivity of the human eye (MfE 1994). However, although the beam attenuation coefficient c at 555 nm can be derived from BD by equation 13, the value of b cannot be properly estimated by difference from c and the absorption coefficient measured at 555 nm. Measuring total absorption (a) is difficult because of scattering by particles, unlike CDOM absorption on a filtrate, and therefore it is preferable to estimate a and b from measurements of Kd and R (following Kirk 1994b). The vertical attenuation coefficients for both upward and downward irradiance are needed to apply this method.

(8) It may be feasible to measure total absorbance, on unfiltered samples, which would require a scattering correction and a different type of equipment.

(9) Monitor for a full year the parameters relevant for the water clarity and the attenuation of light as it passes though the water, with monthly samplings, intended to cover the range of conditions which are needed for a proper assessment of the interrelations of water clarity, the inherent optical properties c, a and b, and phytoplankton biomass, CDOM, turbidity and total suspensoids. One of the questions to be examined is “to what extent are changes in Secchi disk clarity related to changes in chlorophyll a concentration and in CDOM?” Absorbance (as a proxy for CDOM), light penetration (Kd), Secchi depth (black disk visibility if available), R, and the mean concentration of chlorophyll a in the euphotic zone should be measured simultaneously on each

sampling occasion. The vertical attenuation coefficients for both upward and downward irradiance are needed.

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Appendix 1. Data Tables

Table 1. Results of irradiance measurements at the center lake site. The distance between the two sensors is 2.72 m and there is 0.53 m between the top of the metal frame and the top sensor. Mode: Instanteneous. % Light is that at the lower sensor compared with the upper sensor.

Secchi depth = 5.25 m

top bar depth (m)	I_1 CH1	I_2 CH2	% light	sensor depth (m)	LN(I_1) CH1	sensor depth (m)	LN(I_2) CH2	interval K_d (m^{-1})	interval mean depth
0.01	110	748	15	3.26	4.70	0.54	6.62	0.70	1.9
1	115	200	58	4.25	4.74	1.53	5.30	0.20	2.89
2	68	222	31	5.25	4.22	2.53	5.40	0.43	3.89
3	35	167	21	6.25	3.56	3.53	5.12	0.57	4.89
4	20.5	96	21	7.25	3.02	4.53	4.56	0.57	5.89
5	10.7	48	22	8.25	2.37	5.53	3.87	0.55	6.89
6	7.2	31.5	23	9.25	1.97	6.53	3.45	0.54	7.89
7	4.5	19.9	23	10.25	1.50	7.53	2.99	0.55	8.89
8	1.6	7.4	22	11.25	0.47	8.53	2.00	0.56	9.89
9	1.6	4.2	38	12.25	0.47	9.53	1.44	0.35	10.89
10	0.9	3.2	28	13.25	-0.11	10.53	1.16	0.47	11.89
11	0.22	1.3	17	14.25	-1.51	11.53	0.26	0.65	12.89
12	0.34	1.2	28	15.25	-1.08	12.53	0.18	0.46	13.89
13	0.17	0.68	25	16.25	-1.77	13.53	-0.39	0.51	14.89
14	0.12	0.43	28	17.25	-2.12	14.53	-0.84	0.47	15.89
15	0.08	0.29	28	18.25	-2.53	15.53	-1.24	0.47	16.89
16	0.05	0.18	28	19.25	-3.00	16.53	-1.71	0.47	17.89
17	0.03	0.12	25	20.25	-3.51	17.53	-2.12	0.51	18.89
		average	27			Average K_d for segments		0.50	
						excluding outliers		0.52	

Table 2. Results of irradiance measurements at the center lake site. The distance between the two sensors is 2.72 m and there is 0.53 m between the top of the metal frame and the top sensor. Mode: 20 s average. % Light is that at the lower sensor compared with upper sensor.

Secchi depth = 5.25 m

top bar depth (m)	I_1 CH1	I_2 CH2	% light	sensor depth (m)	LN(I_1) CH1	sensor depth (m)	LN(I_2) CH2	interval K_d (m^{-1})	interval mean depth
0.01	190	1135	17	3.26	5.25	0.54	7.03	0.66	1.9
1	124	495	25	4.25	4.82	1.53	6.20	0.51	2.89
2	73	313	23	5.25	4.29	2.53	5.75	0.54	3.89
3	39.9	160	25	6.25	3.69	3.53	5.08	0.51	4.89
4	22.9	97.8	23	7.25	3.13	4.53	4.58	0.53	5.89
5	13.9	59.9	23	8.25	2.63	5.53	4.09	0.54	6.89
6	8.13	33.75	24	9.25	2.10	6.53	3.52	0.52	7.89
7	4.74	19.22	25	10.25	1.56	7.53	2.96	0.51	8.89
8	2.75	10.48	26	11.25	1.01	8.53	2.35	0.49	9.89
9	1.58	4.52	35	12.25	0.46	9.53	1.51	0.39	10.89
10	0.98	1.82	54	13.25	-0.02	10.53	0.60	0.23	11.89
11	0.49	0.72	68	14.25	-0.71	11.53	-0.33	0.14	12.89
		average	31			Average K_d for segments		0.46	
						excluding outliers		0.52	

Table 3. Results of irradiance measurements at the Iveagh Bay (about 25 m depth). The distance between the two sensors is 2.72 m and there is 0.53 m between the top of the metal frame and the top sensor. Mode: 20 s average. % Light is that at the lower sensor compared with upper

Secchi depth = 5.30 m

top bar depth (m)	I_1 CH1	I_2 CH2	% light	sensor depth (m)	LN(I_1) CH1	sensor depth (m)	LN(I_2) CH2	interval K_d (m^{-1})	interval mean depth
0.01	174	1070	16	3.26	5.16	0.54	6.98	0.67	1.9
1	81	430	19	4.25	4.39	1.53	6.06	0.61	2.89
2	19	49	39	5.25	2.94	2.53	3.89	0.35	3.89
3	25	92	27	6.25	3.22	3.53	4.52	0.48	4.89
4	15.4	44.5	35	7.25	2.73	4.53	3.80	0.39	5.89
5	6.5	25.5	25	8.25	1.87	5.53	3.24	0.50	6.89
6	6.4	26.3	24	9.25	1.86	6.53	3.27	0.52	7.89
7	3.66	15.5	24	10.25	1.30	7.53	2.74	0.53	8.89
8	1.85	7.21	26	11.25	0.62	8.53	1.98	0.50	9.89
9	0.98	3.38	29	12.25	-0.02	9.53	1.22	0.46	10.89
10	0.66	2.33	28	13.25	-0.42	10.53	0.85	0.46	11.89
11	0.396	1.41	28	14.25	-0.93	11.53	0.34	0.47	12.89
12	0.265	0.95	28	15.25	-1.33	12.53	-0.05	0.47	13.89
		average	27				Average K_d for segments	0.49	
							excluding outliers	0.49	

Table 4. Results of irradiance measurements at Cashmere Bay. The distance between the two sensors is 2.72 m and there is 0.53 m between the top of the metal frame and the top sensor. Mode: 20 s average. % Light is that at the lower sensor compared with upper sensor.

Secchi depth = 4.18 m

top bar depth (m)	I_1 CH1	I_2 CH2	% light	sensor depth (m)	LN(I_1) CH1	sensor depth (m)	LN(I_2) CH2	interval K_d (m^{-1})	interval mean depth
0.01	162	1007	16	3.26	5.09	0.54	6.91	0.67	1.9
1	82	525	16	4.25	4.41	1.53	6.26	0.68	2.89
2	40.9	264	15	5.25	3.71	2.53	5.58	0.69	3.89
3	18.3	120	15	6.25	2.91	3.53	4.79	0.69	4.89
4	6.9	35	20	7.25	1.93	4.53	3.56	0.60	5.89
5	4.4	32	14	8.25	1.48	5.53	3.47	0.73	6.89
6	1.4	8	18	9.25	0.34	6.53	2.08	0.64	7.89
7	1.2	7.9	15	10.25	0.18	7.53	2.07	0.69	8.89
		average	16				Average K_d for segments	0.67	

Table 5. Summary of K_d estimates at center lake, Iveagh Bay and Cashmere Bay.
Average 1 is for each site separate, and average 2 is for center lake and Iveagh Bay combined.

Measurement		Average 1	Average 2	Secchi	SD*K_d
Center Lake, series 1, sensor 1	0.51	0.54	0.53	5.25	2.83
Center Lake, series 1, sensor 2	0.51				
Center Lake, series 1, mean of intervals	0.52				
Center Lake, series 2, sensor 1	0.54				
Center Lake, series 2, sensor 2	0.63				
Center Lake, series 2, mean of intervals	0.52				
Iveagh Bay, series 1, sensor 1	0.51	0.51		5.3	2.71
Iveagh Bay, series 1, sensor 2	0.53				
Iveagh Bay, series 1, mean of intervals	0.49				
Cashmere Bay, series 1, sensor 1	0.74	0.72		4.18	3.01
Cashmere Bay, series 1, sensor 2	0.74				
Cashmere Bay, series 1, mean of intervals	0.67				