

Title

The Specific Inherent Optical Properties of Three Sub-tropical and Tropical Water Reservoirs in Queensland, Australia.

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Abstract

The underwater light climate, which is a major influence on the ecology of aquatic systems, is affected by the absorption and scattering processes that take place within the water column. Knowledge of the Specific Inherent Optical Properties (SIOPs) of water quality parameters and their spatial variation is essential for the modelling of underwater light fields and remote sensing applications. We measured the SIOPs and water quality parameter concentrations of three large inland water impoundments in Queensland, Australia. The measurements ranged from 0.9–42.7 $\mu\text{g l}^{-1}$ for chlorophyll *a* concentration, 0.9–170.4 mg l^{-1} for tripton concentration, 0.36–1.59 m^{-1} for $a_{CDOM(440)}$ and 0.15–2.5 m for Secchi depth. The SIOP measurements showed that there is sufficient intra-impoundment variation in the specific absorption and specific scattering of phytoplankton and tripton to require a well distributed network of measurement stations to fully characterise the SIOPs of the optical water quality parameters. While significantly different SIOP sets were measured for each of the study sites the measurements were consistent with published values in other inland waters. The multiple measurement stations were allocated into optical domains as a necessary step to parameterise a semi-analytical inversion remote sensing algorithm. This paper also addresses the paucity of published global inland water SIOP sets by contributing Australian SIOP sets to allow international and national comparison.

Introduction

Water resource managers have the responsibility to deliver water of sufficient quality to urban, agricultural and industrial users as well as maintaining the recreational and ecological amenity of the inland water bodies under their control. To deliver these objectives it is critical that they monitor and maintain the quality of the water in their storage reservoirs. In addition, recent studies have shown that inland water bodies have a disproportionate effect on the on the global carbon cycle with water bodies that are supersaturated with carbon dioxide consequently emitting it to the atmosphere (Cole et al., 2007). The higher carbon dioxide concentrations in tropical and subtropical lakes have been attributed to higher rates of respiration (Kosten et al., 2010). Remote sensing is an essential tool to understand the spatial distribution of the factors involved in the ecology of aquatic systems but its application to tropical and sub-tropical inland impoundments has been limited.

The underwater light climate, which is a major influence on the ecology of aquatic systems, is affected by the absorption and scattering processes that take place within the water column. Quantifying the influence of the various absorption and scattering agents within the water allows the light climate to be simulated for ecological studies or inverted to assist in the monitoring of water quality parameters. Optical remote sensing has been used to retrieve water quality parameters such as the concentrations of chlorophyll *a* and other pigments, tripton (the non-algal particles of the suspended particulate matter), and coloured dissolved organic matter (CDOM), to model and monitor dynamic environmental processes. The remotely sensed reflectance spectrum is a result of the cumulative interactions of light with the water itself and the water quality parameters. To retrieve the water quality parameter concentrations it is necessary to invert the reflectance spectrum. The water quality parameter concentrations and the reflectance spectrum are linked by the inherent optical properties (IOPs) of the water. These IOPs have magnitudes that are independent of the geometric structure of the light field. The absorption coefficient *a* describes the chances of a photon being absorbed, the scattering coefficient *b* describes the chances of a photon being scattered and the volume scattering function (VSF) $\beta(\theta)$ describes the probability of a scattered photon being scattered in a particular direction. For practical purposes the latter two IOPs are combined into the backscattering parameter (b_b) which describes the probability of a photon being scattered more than 90° from its original path. Any successful semi-analytic inversion approach needs to relate the water leaving reflectance to the IOPs and then the IOPs to the

water quality parameter concentrations. The IOPs and water quality parameter concentration relationship can be established by normalising the IOPs by the relevant water quality parameter concentration to calculate the Specific Inherent Optical Properties (SIOPs).

With the exception of northern Europe in general and Dutch lakes in particular (Dekker et al., 1992; Hakvoort et al., 2002; Vos et al., 2003; Rijkeboer et al., 1997) there is a surprising lack of published SIOP sets given the geographic variety of inland water bodies. There have been isolated or partially complete reports from Asia (Zhang et al., 2007), Africa (Okullo et al., 2007), North America (Boss et al., 2007) and Australia (Kirk, 1994; Jupp et al., 1994; Kirk, 1986). This situation may exist because of the logistical effort involved in deploying the appropriate light-measuring instruments *in situ*. This paper aims to publish a selection of Australian SIOP sets to allow comparison with other inland waters.

Study Sites

The IOPs were measured in three water storages in north-eastern Australia, Wivenhoe Dam (Lake Wivenhoe, 27° 21' S, 152° 36' E), Fairbairn Dam (Lake Maraboon, 23° 42' S, 148° 02' E) and Burdekin Falls Dam (Lake Dalrymple, 20° 37' S, 147° 0' E). The major geographic parameters of the three sites are shown in Table 1.

Table 1 The key geographic parameters of the three study sites.

Study site	Storage Capacity (ML)	Maximum Depth	Feeding River(s)	Inundated Area at Full Supply Level (Ha)	Mean Rainfall (mm/yr)	Evaporation (mm/yr)
Wivenhoe Dam *	1,165,000	44.0	Brisbane R	10,940	1000	1600
Fairbairn Dam †	1,300,000	31.7	Nogoa R	15,000	600	2000
Burdekin Falls Dam †	1,860,000	40.0	Burdekin R Cape R Belyando/Suttor R	22,000	600	2400

*(South East Queensland Water Corporation Ltd, 2005), † (Sunwater, 2005)

Wivenhoe Dam (Figure 1) is the principal source of drinking water for the city of Brisbane in south east Queensland. It receives inflows from the Upper Brisbane River as well as controlled releases from Somerset Dam which controls the Stanley River. It has a catchment of 7020 km² that is dominated by grazing (>50%) and natural vegetation (20%) (Burford et al., 2006). The catchment receives rainfall of approximately 1000 mm/yr mainly falling over the summer months.

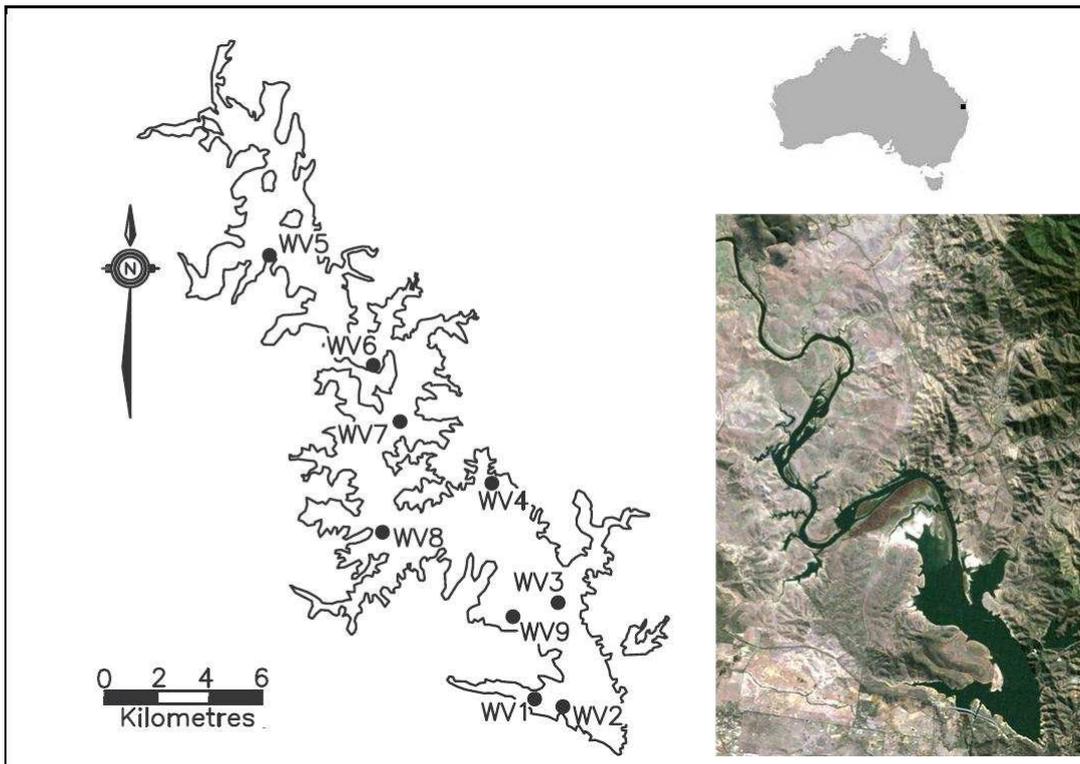


Figure 1 Location of the SIOP sample sites for the July 2007 fieldwork activities on Wivenhoe Dam, Australia. The left hand image shows the calculated full supply level and the right hand side shows a true colour Landsat 5 Thematic Mapper (TM) image, at the same scale captured on 16th July 2007. Note the reduced water extent at the time of the fieldwork activities.

The Nogoia River has a catchment of 27,130 km² and before being blocked by Fairbairn Dam (Figure 2) it had a mean annual sediment load of 1.23 Mt. It forms one of the four major tributaries to the Fitzroy River and it carries the highest sediment load (Joo et al., 2005). The predominant land use in the catchment is grazing with small portions of dryland and irrigated cropping. The catchment receives rainfall of approximately 600 mm/yr mainly falling over the summer months.

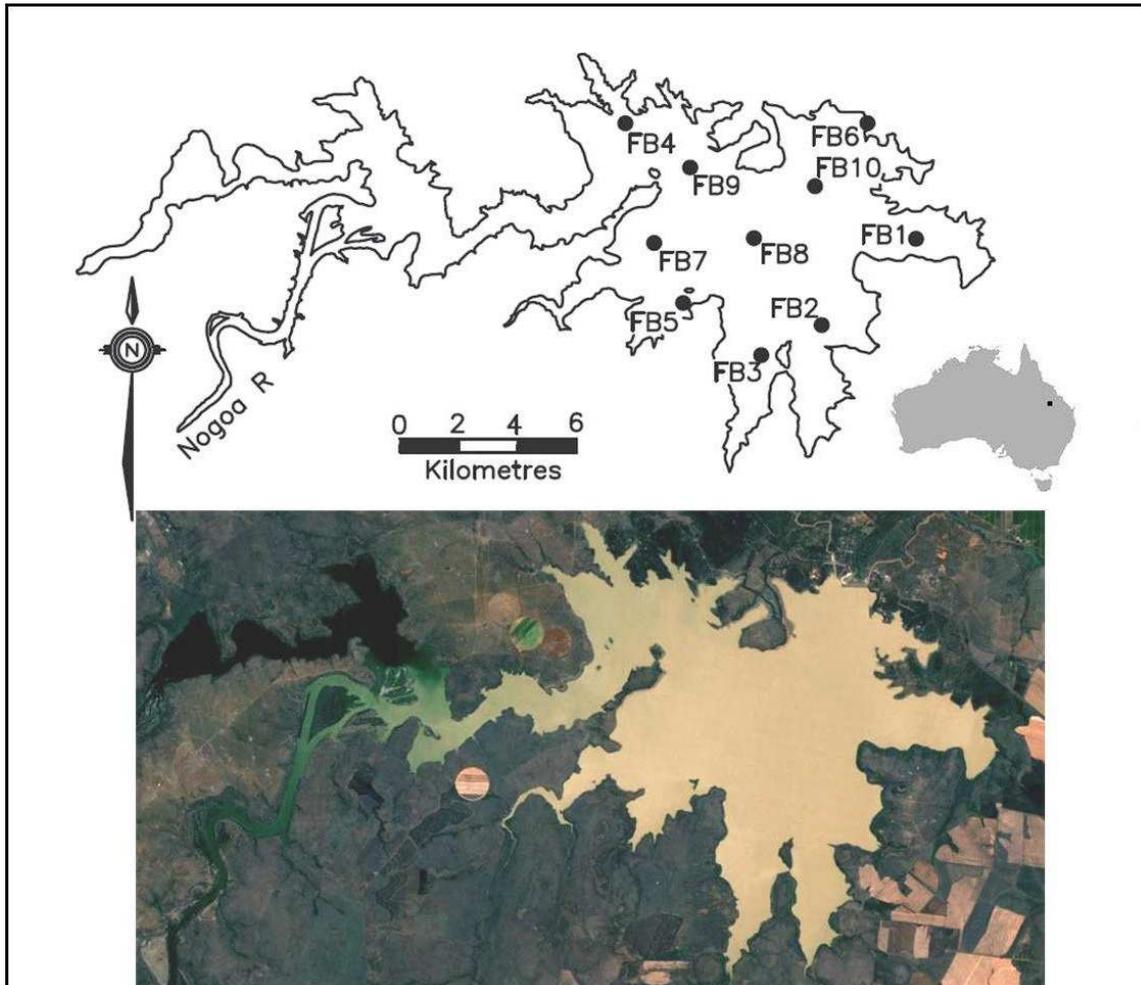


Figure 2 Location of the SIOP sample sites for the October 2008 fieldwork activities on Fairbairn Dam, Australia. The top image shows the calculated full supply level and the bottom image shows a Landsat 5 TM true colour image at the same scale as the map, captured on 3rd November 2008.

The Burdekin Falls Dam (Figure 3) receives inputs from four major sub-catchments that cover a total area of 114,000 km². From the north the Burdekin River has its origin in tropical rainforest but primarily flows through tropical savannah. From the west the lake is fed from the Cape River which rises in reasonably steep sedimentary country and then flows through flat less erodible areas. The Belyando and Suttor Rivers meet just beyond the inundated area and feed the lake from the south. The Belyando River and Suttor Rivers suffer from persistent turbidity as they flow slowly over clay soils (O'Reagain et al., 2005). During full flow conditions the former river takes on a grey colour and the latter red. It is estimated that the dam traps 88% of the sediment that flows in from the tributaries during flow events with the bulk of sediment being transported by the Burdekin River (Bainbridge et al., 2006b; Bainbridge et al., 2006a). However the majority of the turbidity in the water during no flow conditions is associated with the fine clays that are transported from the south (O'Reagain et

al., 2005). The impoundment is split into an upper and lower basin by a narrow neck of land situated between BFD9 and BFD11.

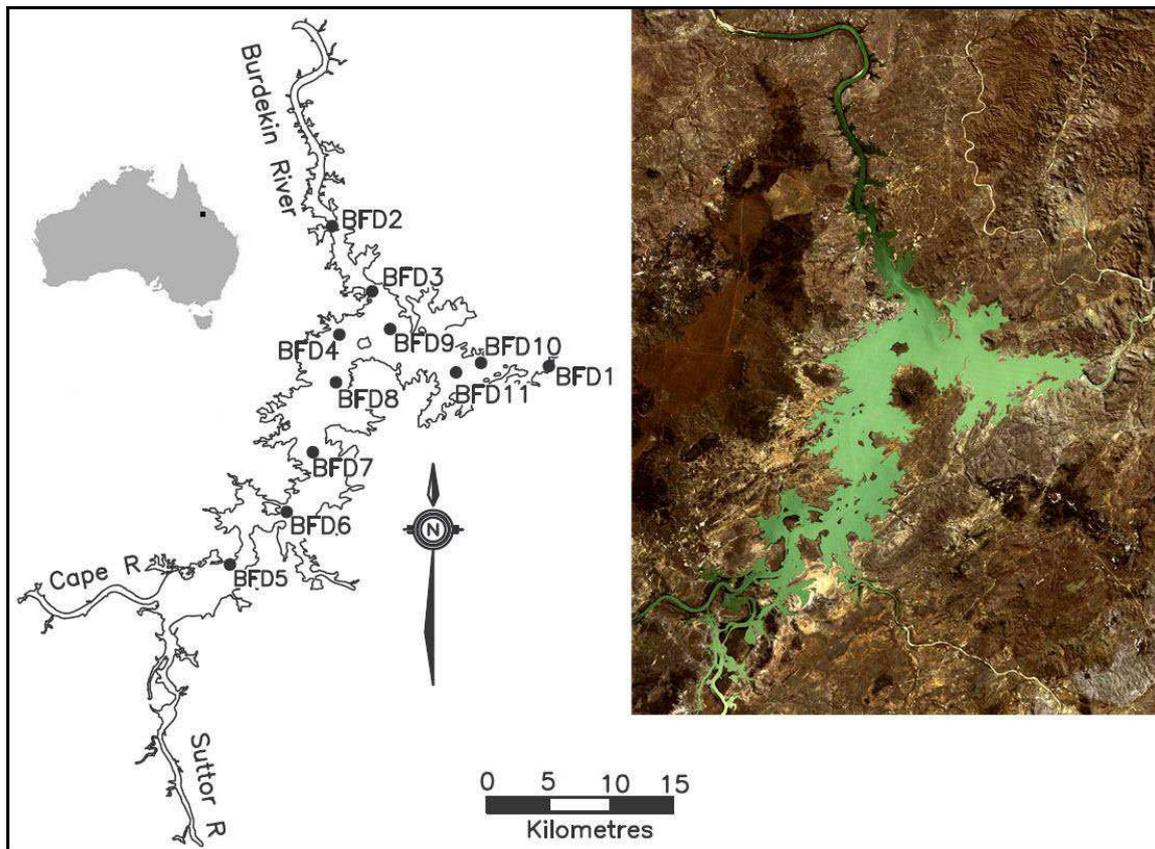


Figure 3 Location of the SIOP sample sites for the October 2008 fieldwork activities on Burdekin Falls Dam, Australia. The left hand image shows the calculated full supply level and the right hand image shows a Landsat 5 TM true colour image at the same scale as the map, captured on 22nd August 2008.

Materials and Methods

In situ Measurements

The field data were collected in the Australian winter of 2007 (July) and the spring of 2008 (October), which represent the beginning and end of a mid-year dry season for each catchment. For the three years prior to the fieldwork Fairbairn Dam and Burdekin Falls Dam catchments had received their expected rainfall but the Wivenhoe Dam catchment had received only 64% of its expected rainfall (Commonwealth Bureau of Meteorology, 2009).

Table 2 Table of in situ data measured at the three study sites.

Study site	Fieldwork dates	Measurement Stations	Water quality parameter Concentrations	IOP Measurements
Wivenhoe Dam	3-4 July 2007	9	Yes	Yes
Fairbairn Dam	8-10 Oct 2008	10	Yes	Partial
Burdekin Falls Dam	13-15 Oct 2008	11	Yes	Yes

The following absorption properties were measured using the *WET Labs* absorption and attenuation meter (*ac-9*) (WET Labs Inc, 2005), a Conductivity-Temperature-Depth (CTD) sensor and the laboratory analysis described below.

- total absorption coefficient a
- the absorption by CDOM a_{CDOM}
- the absorption by tripton a_{TR}
- the absorption by the phytoplankton a_{ϕ}
- the backscattering by the particulate matter b_{bp}

The scattering properties were measured using a HydroScat-6 backscattering sensor (Maffione et al., 1997).

Water Quality Parameter Concentrations

The water samples were taken from approximately 0.3 m below the surface at each station, were kept cool in opaque storage containers and were filtered on the day of collection. The laboratory analysis was carried out by CSIRO Marine and Atmospheric Research Laboratory in Hobart.

Phytoplankton Pigments

Water samples were filtered through a 47 mm diameter GF/F glass-fibre filter (Whatman, nominal pore size; 0.7 μm) and the filter stored in liquid nitrogen. Samples were extracted over 15-18 hours in an acetone solution before analysis by HPLC using a C_8 column and binary gradient system with an elevated column temperature following a modified version of the Van Heukelem and Thomas (2001) method. Pigments were identified by retention time and absorption spectrum from a photo-diode array (PDA) detector and concentrations of pigments were determined from commercial and international standards (Sigma; DHI, Denmark).

Total Suspended Matter

Water samples were filtered through 47 mm diameter pre-weighed Whatman GF/F glass-fibre filters that had been prepared according to the MERIS calibration protocols (Tilstone et al., 2002). After the sample had been filtered, the filter paper was stored flat in a petri-slide (Millipore). After collection, the filter papers were oven-dried at 60°C to constant weight and weighed.

Laboratory Spectrophotometer Measurements of IOPs

Particulate (Algal and Nonalgal) Absorption

Water samples were filtered through a 25mm diameter GF/F glass-fibre filter which was stored flat in liquid nitrogen until analysis. The optical density spectrum was measured over the 200–900 nm spectral range in 1.3 nm increments, using a GBC 916 UV/VIS dual beam spectrophotometer equipped with an integrating sphere. The pigmented material on the sample filter was then extracted using the Kishino *et al.* (1985) method and then the filter was remeasured to determine the optical density of the nonalgal particles. The optical density due to phytoplankton was obtained by the difference between the optical density of the total particulate and nonalgal fractions. The path length amplification effect due to the filter (so-called “ β -factor”) was corrected using the algorithm of Mitchell (1990). A more detailed description of the method is given by Clementson *et al.* (2001).

CDOM Absorption

Water samples were collected in glass bottles and filtered through a 0.22 μm polycarbonate filter (Millipore) using an all glass filtering unit. The filtrate was transferred to a clean glass bottle, preserved with sodium azide (0.5 ml of 10 g l⁻¹ NaN₃ per 100 ml of sample) and kept cool and dark until analysis. Samples were allowed to equilibrate to room temperature before absorbance was measured from 200 to 900 nm using a 10 cm path length quartz cell in a GBC 916 UV/VIS spectrophotometer, with Milli-Q water (Millipore) as a reference. The CDOM absorption coefficients (m⁻¹) were calculated using the equation

$$a_{CDOM} = 2.3 \frac{A_{CDOM}(l)}{l} \quad (1)$$

where $A_{CDOM}(l)$ is the absorbance normalized to zero at 680 nm and l is the cell path length in metres. The spectral slopes are sensitive to the spectral range they are determined over, as subtle differences in the shape of spectra can be overlooked if a broad wavelength interval is used (Helms *et al.*, 2008). As the focus for this work was to characterise the CDOM absorption over the visible spectrum rather than provide compositional insights the spectra were then fitted with a single exponential function over the range 350–680 nm.

Field Measurements of Bulk IOPs

Instruments

The bulk IOPs were measured *in situ* using a CTD sensor, *ac-9* absorption and attenuation meter and a Hydroscat-6 backscattering sensor. The *ac-9* dual beam spectrophotometer consisted of two flow tubes to measure the attenuation and the absorption. In the non-reflecting attenuation flow tube all photons that are scattered were absorbed by the sides of the tube, whereas the absorption tube was highly reflective so that those photons were reflected back into the detector at the end of the tube. This meant that the photons were only removed from the stream by absorption by the medium. The *ac-9* measured at nine wavelengths (412, 440, 488, 510, 532, 555, 650, 676 and 715 nm). The Hydroscat-6 emitted light at six wavelengths and then measured the amount of light that was returned at a backscatter angle of 140° (Maffione et al., 1997). For the Wivenhoe Dam measurements the Hydroscat-6 measured at wavelengths of 420, 442, 488, 550, 676 and 700 nm. For the other water bodies the 700 nm wavelength was replaced with a wavelength of 852 nm.

Deployment

Due to the restricted vessel size available for the field work it was not practical to deploy the CTD, *ac-9* and HydroScat-6 instruments simultaneously within the water column. When the sampling craft was on station a small electric bilge pump was used to continuously sample the water from 0.5 m below the surface into a de-bubbling chamber. From there it was gravity fed successively through a CTD sensor, *ac-9* and into a black PVC container. During the July 2007 fieldwork an *ac-9* with a 10cm flow tube was used. This instrument was not available for the October 2008 field campaign and it was replaced for that fieldtrip with an *ac-9* with a 25 cm flow tube. The backscattering properties were measured using a HydroScat-6 (Maffione et al., 1997) suspended in the black PVC container at Wivenhoe Dam and deployed directly into the lake at the other sites.

Data Corrections

Simultaneous measurement of the absorption and attenuation of the water was required as the raw Hydroscat-6 backscatter observations contain systematic errors associated with the water and water quality parameter absorption. Similarly because the absorption of water is affected by the salinity and temperature of water (Pegau et al., 1993) corrections must be made to the *ac-9* absorption measurements before they can be used to correct the backscatter observation.

The effect of temperature and salinity on the absorption of water was corrected using the Pegau *et al.* (1997) method. As the three study sites are freshwater impoundments the effect of salinity was negligible and a correction was not applied. The attenuation coefficient is the sum of the absorption and scattering coefficients. The effect on the attenuation coefficient in the visible and NIR regions was the same as that on the absorption coefficient as the scattering coefficient is only affected by temperature or salinity in the ultraviolet wavelengths (WET Labs Inc, 2005).

The absorption tube of the *ac-9* was highly reflective so that scattered photons were reflected back into the detector at the end of the tube. In practice photons that are scattered backwards do not reach the detector. There are however some losses due to the imperfect reflection of the flow tube and some photons reach the end of the tube but evade the detector (Mueller *et al.*, 2003; Kirk, 1992). The Zaneveld *et al.* (1994) correction for this effect was applied. The very high turbidity of the Fairbairn Dam water meant that water exceeded the dynamic range of the attenuation side of the *ac-9* with a 25 cm flow tube and these measurements were unusable.

In high light-attenuating waters, the measured backscatter can be appreciably lower than the true backscatter. A correction for this effect was applied (Dana *et al.*, 2002). A separate measurement of the backscattering due to phytoplankton cells was not feasible. It was necessary to make an assumption about the ratio of the concentration of chlorophyll *a* to the dry weight of phytoplankton. A value of $1 \mu\text{g l}^{-1}$ of chlorophyll *a* being approximately equal to 0.07 mg l^{-1} total suspended material (TSM) was measured for Dutch lakes (Buiteveld, 1995). The backscattering was apportioned using this assumption.

Calculation of SIOPs

The chlorophyll *a* specific absorption co-efficient of phytoplankton (a_{ϕ}^*) was obtained by normalising the absorption due to phytoplankton by the chlorophyll *a* concentration. Similarly, the tripton mass specific absorption co-efficient (a_{TR}^*) was obtained by normalising the absorption due to non-algal particles by the weight of the TSM less the weight of the phytoplankton.

The specific backscattering spectra were calculated by normalising the apportioned tripton and phytoplankton fractions by their respective dry weights.

Results

The ranges of the water quality parameters are shown in Table 3.

Table 3 Range (Mean and Standard Deviation) of Chlorophyll a , Tripton, $a_{CDOM}(440)$ and Secchi Depth for each study site.

Study site	Chlorophyll a ($\mu\text{g l}^{-1}$)	Tripton (mg l^{-1})	$a_{CDOM}(440)$ (m^{-1})	Secchi Depth (m)
Wivenhoe Dam	5 – 42.7 (18.74 ± 15.57)	0.9 – 11.2 (4.99 ± 3.06)	0.36 – 0.65 (0.47 ± 0.11)	0.9 – 2.5 (1.72 ± 0.52)
Burdekin Falls Dam	2.8 – 7.7 (4.74 ± 1.54)	5.6 – 10.3 (6.78 ± 1.31)	0.88 – 1.27 (1.05 ± 0.11)	0.9 – 1.3 (1.04 ± 0.13)
Fairbairn Dam	0.9 – 2.9 (1.68 ± 0.71)	149.0 – 170.4 (160.9 ± 6.2)	1.16 – 1.59 (1.24 ± 0.16)	0.15 – 0.2 (0.18 ± 0.03)

Wivenhoe Dam

The specific absorption spectra for the Wivenhoe Dam samples are shown in Figure 4.

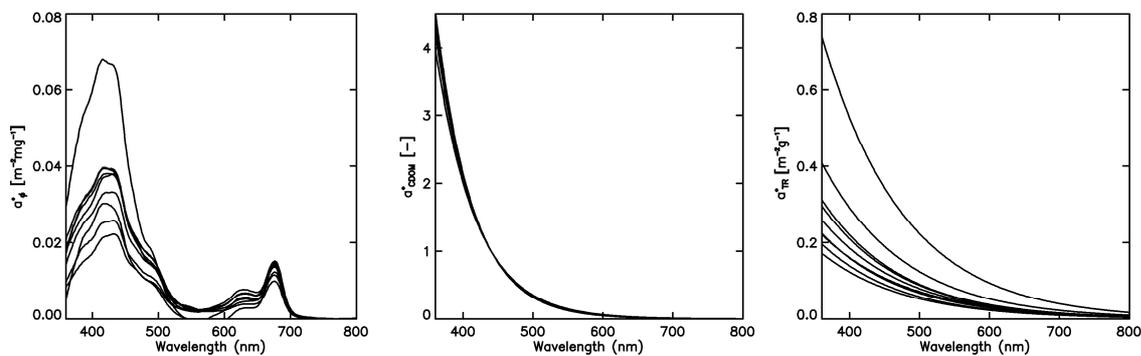


Figure 4 SIOPs for Wivenhoe Dam: The left hand graph shows the chlorophyll a specific absorption spectra of phytoplankton (ϕ), the middle graph the specific absorption of coloured dissolved organic matter (CDOM) and the right hand graph the mass specific absorption of tripton (TR)

The specific absorption spectra for CDOM were fitted to the model

$$a_{CDOM}^* = a_{CDOM}^*(\lambda_0) \exp(-S(\lambda - \lambda_0)) \quad (2)$$

with $\lambda_0 = 440\text{nm}$ and $a_{CDOM}^*(\lambda_0) = 1$, by definition, and S is the spectral slope. There was very little variation between stations with the spectral slopes being in the range of $0.0173\text{-}0.0190 \text{ nm}^{-1}$ with a mean spectrum slope of 0.0185 nm^{-1} . This is marginally outside the range of $0.012\text{-}0.018 \text{ nm}^{-1}$ for a variety of Australian inland waters reported by Kirk (1994). The wavelength range that these slopes were calculated over was not described.

The tripton mass specific absorption spectra were fitted to the model

$$a_{TR}^* = a_{TR}^*(\lambda_0) \exp(-S(\lambda - \lambda_0)) \quad (3)$$

with $\lambda_0 = 550$ nm. The spectral slopes ranged from 0.0080 – 0.0088 nm^{-1} with a mean spectrum slope of 0.0085 nm^{-1} and $a_{TR}^*(550)$ ranged from 0.035 – 0.145 m^2g^{-1} with a mean value of 0.062 m^2g^{-1} .

The specific backscattering of tripton and phytoplankton were fitted to the standard model (Morel et al., 1977):

$$b_b^*(\lambda) = b_b^*(\lambda_0) \left(\frac{\lambda}{\lambda_0} \right)^\gamma, \quad \lambda_0 = 542 \text{ nm} \quad (4)$$

The measured parameters of the specific backscattering are given in Table 4.

Table 4 The parameters describing the tripton and phytoplankton backscattering spectra for the Wivenhoe Dam stations. Also listed are the mean backscattering ratio ($b_{bp}:b_p$) and the correlation coefficient of the power model fitted to the six measured wavelengths.

Station	γ	$b_{bTR}^*(\lambda_0)$ (m^2g^{-1})	$b_{b\phi}^*(\lambda_0)$ (m^2mg^{-1})	Mean $b_{bp}:b_p$	R^2
WV1	-0.91	0.021	0.002	0.014	0.97
WV2	-1.00	0.008	0.001	0.014	0.87
WV3	-0.92	0.014	0.001	0.014	0.99
WV4	-0.88	0.013	0.001	0.013	0.99
WV5	-0.49	0.009	0.001	0.013	0.74
WV6	-0.76	0.008	0.001	0.013	0.94
WV7	-0.86	0.008	0.001	0.013	0.92
WV8	-0.93	0.010	0.001	0.014	0.99
WV9	-0.93	0.007	0.001	0.013	0.98

Burdekin Falls Dam

The specific absorption spectra for the Burdekin Falls Dam samples are shown in Figure 5.

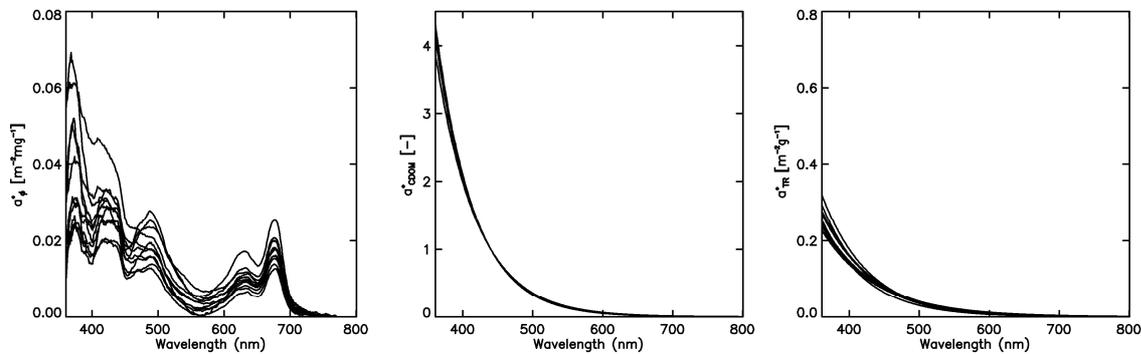


Figure 5 SIOPs for Burdekin Falls Dam: The left hand graph shows the chlorophyll *a* specific absorption spectra of phytoplankton (ϕ), the middle graph the specific absorption of coloured dissolved organic matter (CDOM) and the right hand graph the mass specific absorption of tripton (TR)

It is clear that there is very little variation in the CDOM specific absorption for the Burdekin Falls Dam sample stations. The spectral slopes ranged from 0.0171 – 0.0185 nm⁻¹ with a mean spectrum slope of 0.0182 nm⁻¹.

The spectral slopes for the specific tripton absorption ranged from 0.0123 – 0.0153 nm⁻¹ with a mean spectrum slope of 0.0136 nm⁻¹ and $a^*_{TR}(550)$ ranged from 0.014 – 0.022 m²g⁻¹ with a mean value of 0.019 m²g⁻¹.

The measured parameters of the specific backscattering are given in Table 5.

Table 5 The parameters describing the tripton and phytoplankton backscattering spectra for the Burdekin Falls Dam stations. Also listed are the mean backscattering ratio and the correlation coefficient of the power model fitted to the six measured wavelengths.

Station	γ	$b^*_{bTR}(\lambda_0)$ (m ² g ⁻¹)	$b^*_{bp}(\lambda_0)$ (m ² mg ⁻¹)	Mean $b_{bp}:b_p$	R ²
BFD1	-1.47	0.049	0.004	0.093	0.95
BFD2	-1.27	0.029	0.002	0.039	0.93
BFD3	-1.31	0.031	0.002	0.042	0.93
BFD4	-1.57	0.038	0.003	0.041	0.96
BFD5	-1.14	0.035	0.003	0.043	0.92
BFD6	-1.32	0.037	0.003	0.041	0.94
BFD7	-1.41	0.035	0.003	0.045	0.95
BFD8	-1.45	0.039	0.003	0.048	0.95
BFD9	-1.47	0.036	0.003	0.049	0.95
BFD10	-1.54	0.061	0.004	0.074	0.95
BFD11	-1.57	0.056	0.004	0.076	0.96

Fairbairn Dam

The amount of suspended material in the Fairbairn Dam samples extracted from the water onto a filter was too great to allow laboratory measurement of the phytoplankton or tripton absorption. The specific absorption spectra of tripton and CDOM for the Fairbairn Dam samples are shown in Figure 6.

The spectral slopes for CDOM ranged from 0.0156 – 0.0181 nm⁻¹ with a mean spectrum slope of 0.0175 nm⁻¹.

After the *ac-9* data was corrected the absorption of CDOM at the *ac-9* wavelengths was subtracted to leave the absorption of phytoplankton and tripton. Calculations based on the Burdekin Falls Dam SIOP set showed that for the relative concentrations measured at the Fairbairn Dam stations the phytoplankton absorption accounts for approximately 0.3% of the

absorption at 412 nm. Given the error associated with the *in situ* absorption measurements the absorption associated with phytoplankton could be safely disregarded. The tripton absorption model was then fitted to the tripton absorption spectra. The spectral slopes ranged from 0.0086 – 0.0089 nm⁻¹ with a mean spectrum slope of 0.0087 nm⁻¹ and $a_{TR}^*(550)$ ranged from 0.034 – 0.038 m²g⁻¹ with a mean value of 0.036 m²g⁻¹.

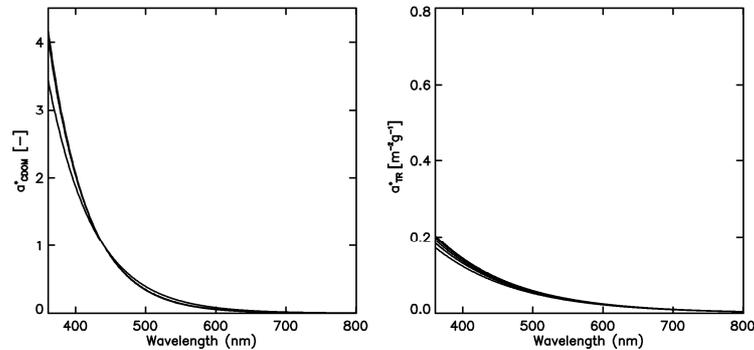


Figure 6 SIOPs for Fairbairn Dam: The left hand graph shows the specific absorption of coloured dissolved organic matter (CDOM) and the right hand graph the mass specific absorption of tripton (TR)

Discussion

Optical Domains

The accuracy of semi-analytic remote sensing algorithms relies on their correct parameterisation with SIOP sets that are appropriate for the water pixel being examined. As horizontal gradients in SIOPs within a water body can exist in some cases the fit between the measured spectrum and the forward model spectrum is used to select the most appropriate SIOP set from a reference group (Dekker et al., 2004; Wettle et al., 2006). If this approach is to be used then it is first necessary to allocate *in situ* measured SIOP spectra into domains based on whether the spectra are likely to be different SIOP populations or are samples from the same SIOP population. Once the SIOP spectra have been allocated into domains it is appropriate to combine them by averaging to allow for the natural variation associated with biological and environmental parameters and the inherent measurement errors associated with each of the field and laboratory procedures.

Wivenhoe Dam

In general terms there is little difference in the shape of the measured phytoplankton spectra across the water body with the exception of the significantly larger absorption peak observed at 420 nm for WV5. Diurnal variations in a_{ϕ}^* coincide with the diurnal changes in pigmentation and photoprotective pigment contents due to photoadaptation at high irradiance.

The type of change in a_{φ}^* for picoplankton has been shown to vary in different directions if the phytoplankton are living in high or low light conditions (Ohi et al., 2005). This would suggest that even if observations are made at similar times of day to counteract diurnal variations there may be some systematic variation due to the prevailing light conditions. It should be noted that the Secchi depth was a minimum at WV5 and the higher than average peak may be the phytoplankton's response to the low light conditions. The phytoplankton community structure was investigated by examining the relative proportions of the diagnostic pigments measured by the HPLC analysis (Bricaud et al., 2004; Vidussi et al., 2001). The relative proportions of picophytoplankton (<2 μm), nanophytoplankton (2– 20 μm) and microphytoplankton (>20 μm) were estimated. The results should be treated with caution as the equations used to calculate the proportions were based on measurements of marine phytoplankton species. This analysis shows that the WV5 sample was heavily dominated by microphytoplankton (90%) whereas the mean for the other eight samples was 45%.

There was very little variation apparent in the slope of the tripton mass specific absorption. Station WV1 had a substantially larger $a_{TR}^*(550)$ value but this difference may be an artefact of the very low tripton measurement (0.9 mg l^{-1}) for this station, as small measurement errors will have a large effect on the specific absorption when the tripton concentration is very low. The other notable value for $a_{TR}^*(550)$ was recorded at WV5. Previous isotopic and statistical analysis of the Wivenhoe Dam sediments showed that the area around WV5 was dominated by the Neara Volcanics type sediment whereas the remainder of the basin is dominated by the Esk Formation sediment (Douglas et al., 2007). Therefore it is not unreasonable to suspect that the SIOPs of the suspended material may be different for WV5.

There is a possibility that the high values measured for $b_{bTR}^*(542)$ for the WV1 station is due to measurement error rather than any significant difference in the tripton itself. As with the phytoplankton and tripton absorption the values measured for $b_{bTR}^*(542)$ for the WV5 station are the exception. It would appear that the high chlorophyll a concentration and the greater proportion of larger particles associated with microphytoplankton leads to a flattening of the scattering spectra determined for this site. This argument is supported by station WV6 which had similar water quality parameter concentrations but a much lower proportion of microphytoplankton and showed a steeper spectral slope that is consistent with the other measurement stations. Nevertheless, the relatively poor correlation coefficient of the fit suggests that there is a greater uncertainty in this measured value than the others.

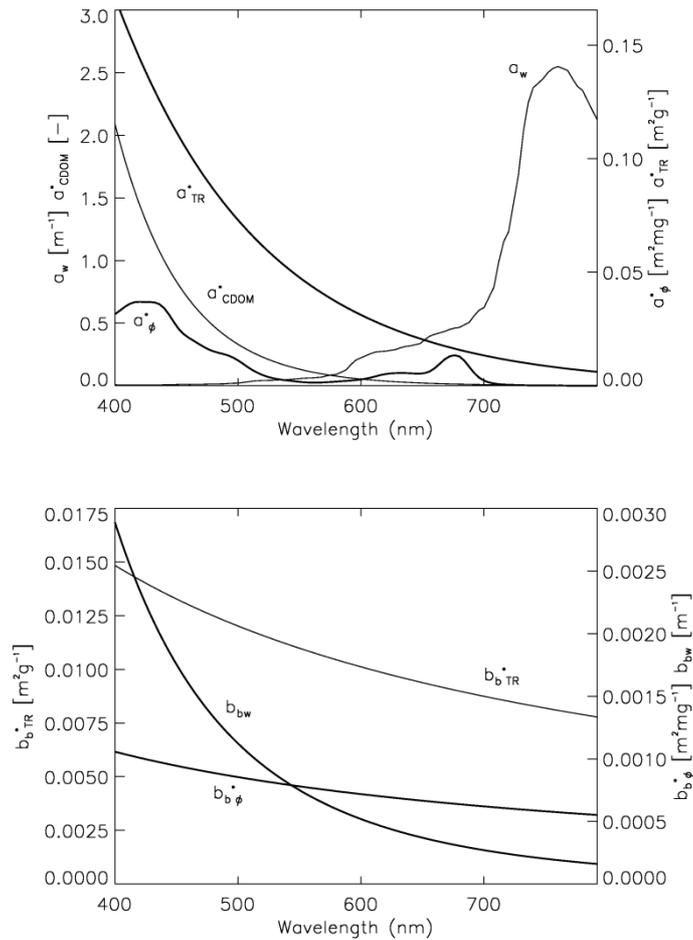


Figure 7 Average SIOPs for Wivenhoe Dam: The upper graph shows the spectral absorption of water (w) and the specific absorption spectra of chlorophyll $a(\phi)$, tripton (TR) and coloured dissolved organic matter ($CDOM$). The lower shows the spectral backscattering of water (w) and the specific backscattering spectra of chlorophyll $a(\phi)$ and tripton (TR).

Stations WV1 and WV5 showed significant differences in SIOP shape and scale between themselves and with respect to the other measurement stations. The remaining seven measured stations show a close resemblance in all the SIOP spectra measured. The most pronounced difference is in the $a_{TR}^*(550)$ values that range $\pm 20\%$ around their mean. This variation is not insignificant but the similarity in tripton absorption slope and the other SIOP spectra meant that they were considered as being part of the same optical domain. The SIOP spectra from these seven stations were averaged into a single SIOP set (see Figure 7) to characterise the Wivenhoe Dam optical properties.

Burdekin Falls Dam

Different algal groups, and also different physiological states of the same alga, differ quantitatively and qualitatively in pigment composition and hence the specific absorption varies widely between and within organisms (Davies-Colley et al., 1986; Sathyendranath et al., 1987). It is clear from Figure 5 that there are differences in the phytoplankton assemblages within the water body. The absorption maxima observed (ca. 630nm) indicate that the phytoplankton assemblages are dominated by cyanobacteria (Richardson, 1996). Although cyanobacteria are capable of regulating their buoyancy, studies have shown that the dynamics of the mixed layer is the dominant factor in the phytoplankton vertical distribution (Ibelings et al., 1991; Mitrovic et al., 2001). As the water samples were taken in the same time period on each day and the prevailing weather conditions were similar it seems unlikely that this is the cause of the variation. The spectral angle mapper (SAM) was used for an inter comparison of the eleven measured spectra. The comparison was performed with the IDL hierarchical clustering algorithm (ITT Visual Information Solutions, Boulder, CO) using a weighted pair wise average. The phytoplankton absorption spectra clustered into three groups broadly representing the Sutor River basin (BFD5 ,6 and 1), the lower basin (BFD10 and BFD11) and the Burdekin River Basin (BFD2,3,4,7,8 and 9). If the spectra were grouped strictly on location, BFD1 would be grouped with the other lower basin sites.

The tripton mass specific absorption shows a greater range of slope variation but the $a_{TR}^*(550)$ variation was comparable to that observed at Wivenhoe Dam. The modelled slope (S) and $a_{TR}^*(550)$ were used as dimensions in a clustering process. This split the measurements into two groups representing the upper and lower basin.

Among the eleven stations there is a spatial variation in the tripton backscattering spectral slope, $b_{bTR}^*(542)$ and the backscattering ratio values. The lower end of the backscattering ratio values are comparable to values measured in the Fitzroy River (Oubelkheir et al., 2006) but the values measured in the lower basin are approximately double the magnitude. This backscatter ratio is dependent on the real part of the refractive index (Twardowski et al., 2001). The particle size distribution is often approximated with a hyperbolic (Junge-type) distribution but some authors have concluded that this function over-estimates the number of small particles and under-estimates the number of large particles (Risovic, 1993). Depending on the distribution model that is chosen, theoretical studies have shown that the particle size distribution is a significant factor in determining the backscattering ratio (Ulloa et al., 1994)

or only in some ranges of the real part of the refractive index (Twardowski et al., 2001). Notwithstanding this, both models show an increase in the backscattering ratio when particle size distributions are dominated by smaller particles. In general terms terrigenous particles are smaller than biogenic particles (Risovic, 1993) so it is not unreasonable to expect that the backscattering ratio from the Burdekin Falls Dam stations, where tripton dominates, should be larger than those measured at the Wivenhoe Dam sites, where biogenic particles dominate. Previous studies have measured backscattering ratios for riverine water of 0.025-0.07 (Whitlock et al., 1981), 0.041 ± 0.03 for Lake Taihu, China (Ma et al., 2009) and 0.026 ± 0.006 for Southern Frisian Lakes in The Netherlands (Dekker et al., 2002). Observations of the Oslo Fjord returned a mean value of 0.02, approximately 5% of the 630 observations were greater than 0.04 and the largest observations were of the order of 0.12 (Aas et al., 2005). In the latter study there was sufficient evidence for the authors to conclude that the deviations from the typical Petzold (1972) turbid water backscattering ratio were too numerous to ignore and were most likely to be caused by a predominance of small particles. The values observed at Burdekin Falls Dam are at the high end of the modelled ranges and there is a possibility that this is because of some error or incorrect assumption in the correction procedure. The most obvious candidate would be the σ correction for the Hydrosat-6 measurements. As this is an empirically derived relationship fitted to an exponential function there is a possibility that the highly scattering water being measured is outside the bounds of the empirical fit, but a definitive explanation is outside the scope of this paper.

The SIOP spectra of Burdekin Falls Dam displayed a greater within-impoundment variation than that of Wivenhoe Dam. To reduce the number of combinations of SIOPs the effect of remote sensing satellite band position and width was considered. For example a number of the significant differences between the phytoplankton absorption groups occur in parts of the light spectrum that are outside of the MERIS bands. The hierarchical clustering algorithm was rerun using spectra that had been convolved with the MERIS bands. In this case the spectra resolve into two groups broadly centred on the upper and lower basins. This made it logical to characterise the water body using the two optical domains illustrated in Figure 8.

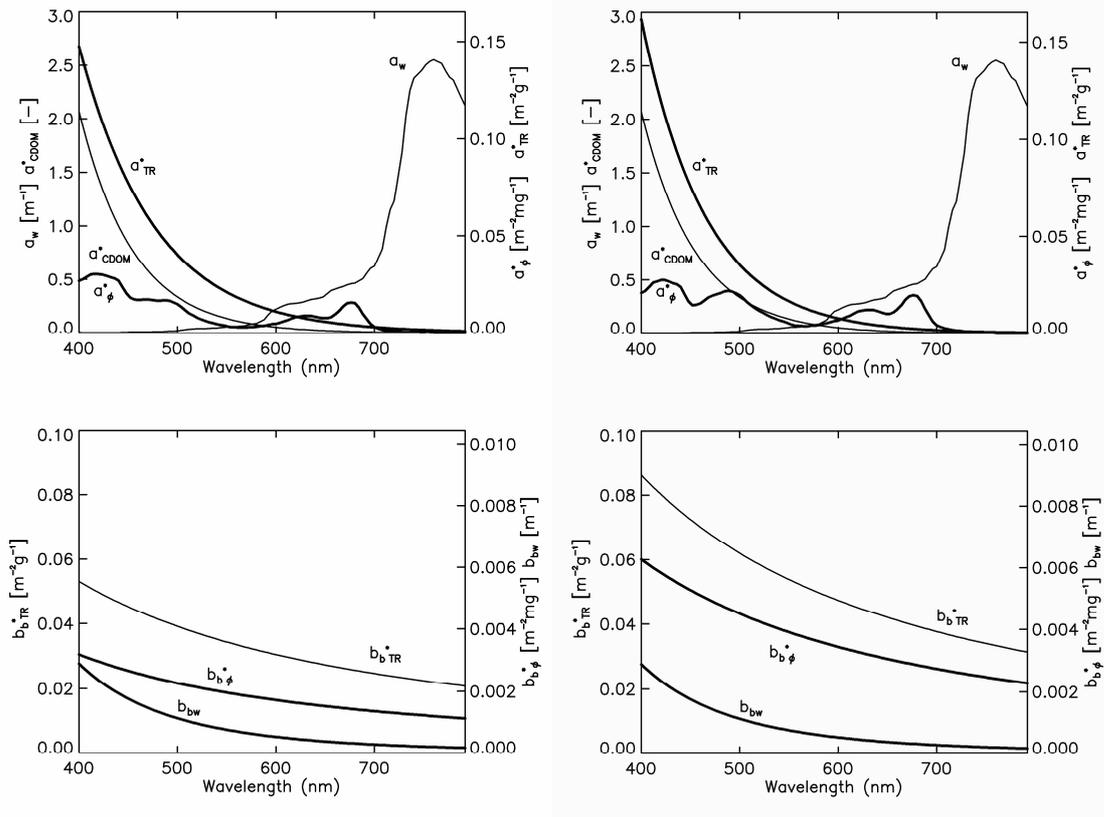


Figure 8 Average SIOPs for Burdekin Falls Dam (left: Upper basin, right: lower basin): The upper graph shows the spectral absorption of water (w) and the specific absorption spectra of chlorophyll $a(\phi)$, tripton (TR) and coloured dissolved organic matter ($CDOM$). The lower shows the spectral backscattering of water (w) and the specific backscattering spectra of chlorophyll $a(\phi)$ and tripton (TR).

Fairbairn Dam

Once again there was very little variation in the specific CDOM absorption for the Fairbairn Dam sample stations with the exception of station FB4. The slope of the CDOM absorption curve has been shown to be inversely proportional the molecular weight of fulvic acids (Hayase et al., 1985; Carder et al., 1989) and is affected by photodegradation (Morris et al., 1997). Loiselle *et al.* (2009) found an increase in the CDOM spectral slope with distance from the main inlet for a subtropical lake. FB4 was exceptional in that it was in the mouth of the main inflow channel and in an area of the water body that was heavily dominated by dead standing timber. It is therefore not unreasonable to expect a difference in spectral slope with respect to the rest of the water body, but it is not possible to conclude whether different molecular qualities or a lack of photodegradation is responsible for the difference.

Representation of Phytoplankton Absorption

The direct comparison of phytoplankton absorption spectra is limited by the predominance of reporting just the spectral graphs without including the underlying numerical spectral data

values. The phytoplankton specific absorption curves are too complex to describe analytically and so many researchers either merely plot or refer to the size of prominent absorption features. The exception is those who adopt the Bricaud et al. (1995) approach. Perhaps an impediment to the wider adoption of this approach has been the large number of parameters (152) required to describe a spectrum. Alternatively, it has been shown that the phytoplankton specific absorption spectra can be modelled as the sum of 10-13 Gaussian curves (Hoepffner et al., 1991; Lohrenz et al., 2003). Such an approach has been used in the past by researchers who have been interested in the connection between these curve amplitudes, full width half magnitudes (FWHMs) and centres and their relationship to auxiliary pigments and species. Notwithstanding these possibilities, on a more prosaic level a list of those three factors will allow any reported phytoplankton specific absorption spectra to be recreated accurately without resorting to scaling from spectral figures or a very large table of parameters.

Each of the final phytoplankton specific absorption spectra were decomposed into thirteen Gaussian bands of the following form:

$$f(\lambda) = a_0 \exp \left[-\ln 2 \left(\frac{2(\lambda - \lambda_0)}{\Delta\lambda_{1/2}} \right)^2 \right] \quad (5)$$

where a_0 is the peak amplitude, λ_0 is the band centre and $\Delta\lambda_{1/2}$ is the FWHM. The band centres were held constant to the initial values of Lohrenz *et al.* (2003) and the other two parameters were varied to obtain the optimal fit using the least squares criterion. The results are shown in Table 6.

Table 6 The optimal modelled parameters describing the chlorophyll *a* specific absorption spectra of phytoplankton for Wivenhoe Dam and Burdekin Falls Dam.

λ_0 (nm)	Wivenhoe Dam		Burdekin Falls Upper		Burdekin Falls Lower	
	a_0 (m ² mg ⁻¹)	FWHM (nm)	a_0 (m ² mg ⁻¹)	FWHM (nm)	a_0 (m ² mg ⁻¹)	FWHM (nm)
376	0.05132	30.5	0.01557	159.5		
409	0.02310	27.6	0.01379	28.7	0.02295	33.5
435	0.03038	35.1	0.01611	30.0	0.02054	28.7
461	0.00025	8.7				
464	0.00889	28.3	0.00344	17.8	0.00507	22.4
490	0.01220	44.8	0.01291	49.1	0.02155	51.8
539	0.00214	41.5	0.00303	41.0	0.00537	40.1
586	0.00212	38.5	0.00308	40.3	0.00435	38.4
622	0.00487	34.3	0.00707	36.2	0.00989	37.4
642	0.00306	24.8	0.00444	26.2	0.00570	27.1
652	0.00083	16.0	0.00057	12.3	0.00089	15.4
675	0.01315	29.2	0.01521	29.7	0.01876	29.3
701	0.00058	53.1	0.00122	56.3	0.00210	59.0

Assumptions Related to Phytoplankton

This study makes two assumptions in relation to phytoplankton properties. Firstly, that the Dutch lakes (Buiteveld, 1995) relationship between chlorophyll *a* concentration and phytoplankton dry weight biomass can be used in other environments and secondly, that the backscattering of phytoplankton has the same spectral shape as that of tripton.

Due to the difficulties associated with calculating a site specific value the Dutch lakes value has been widely used in other environments (Erm et al., 2002; Herlevi, 2002b; Kutser, 2004; Zhang et al., 2009). Even if this ratio was as low as 0.03 to 0.06 as reported for some Finnish lakes (Kutser et al., 2001) the effect on the calculation of the tripton concentration would be negligible for the majority of measured stations and still small for stations WV5-7.

An alternative method to using the second assumption would be to estimate the tripton backscattering from the total backscattering by subtracting previously published chlorophyll *a* specific backscattering of phytoplankton values. Reported backscattering spectra (Ahn et al., 1992; Kutser et al., 2006; Metsamaa et al., 2006) have been measured for laboratory cultured single species. Vaillancourt et al. (2004) found that the chlorophyll *a* specific backscattering increased as cells decreased in size but this was also dependent of the particulate organic carbon to chlorophyll *a* ratio. This ratio varies with species composition and light and nutrient conditions. Not only do the optical properties differ between species,

but the properties of pure cultures will differ from natural assemblages due to the differences in the prevailing light and nutrient conditions. The errors associated with this alternative method are comparable to the assumption that has been made.

Nevertheless, the effect of errors associated with both these assumptions on a final remote sensing algorithm performance is likely to be small as the backscattering of tripton will dominate the scattering processes.

International Comparisons

The description of SIOPs for inland waters in the literature is often incomplete because researchers are either focussing on one particular colour-producing agent or on the remote sensing of water quality parameters. The former case provides a detailed examination of the optical properties of a single water quality parameter to the exclusion of the others and the latter case often shows involves just graphical representations of SIOP sets. Table 7 shows a comparison of the measured Queensland tropical and sub-tropical SIOP values to published values in other environments.

The direct comparison of spectral slopes between studies is difficult if the slopes have been calculated over different spectral ranges, but the present measured values for the spectral slope of the specific absorption of CDOM are comparable to values measured in New Zealand lakes (Davies-Colley et al., 1987) and Lake Superior, North America (Minor et al., 2008)). In general they are larger than mean slopes for Murchison Bay in Lake Victoria (Okullo et al., 2007) , Lake Mälaren, Sweden (Strömbeck et al., 2001), Finnish lakes (Kallio et al., 2005) and Dutch inland waters (Rijkeboer et al., 1997). Values measured in Lake Taihu, China were reported using a hyperbolic model but transformation of those results show the Queensland lakes had spectral slopes that were considerably larger (Zhang et al., 2007). The range of slopes measured in the three lakes is smaller than that measured in a single lake, Laguna Ibeña, Argentina (Loiselle et al., 2009).

1 **Table 7 Comparison of Queensland Dam SIOP values to literature values.**

Location	$a^*_{CDOM} Slope$ (nm^{-1})	<i>Slope Range</i> (nm)	$a^*_{\phi}(670-676)$ (m^2mg^{-1})	$a^*_{TR}(550)$ (m^2g^{-1})	$a^*_{TR} Slope$ (nm^{-1})	$b^*_{bTR}(542)$ (m^2g^{-1})	γ_{TR} (nm^{-1})	$b^*_{b\phi}(620)$ (m^2mg^{-1})	Reference
Wivenhoe Dam	0.0173-0.0190	350-680	0.010-0.014	0.035-0.145	0.0080 – 0.0088	0.008-0.021	0.49-1.00		
Burdekin Falls Dam	0.0171-0.0185	350-680	0.012-0.025	0.014-0.022	0.0123 – 0.0153	0.031-0.061	1.14-1.57		
Fairbairn Dam	0.0156-0.0181	350-680	n.d.	0.034-0.038	0.0086 – 0.0089	n.d.	n.d.		
New Zealand lakes	0.0151-0.0205	280-460	0.01-0.033						(Davies-Colley et al., 1987; Davies-Colley et al., 1986; Belzile et al., 2004) (Minor et al., 2008)
Lake Superior, North America	0.0183-0.0215	290-400							
Murchison Bay, Lake Victoria	0.016 ± 0.001	200-900							(Okullo et al., 2007)
Lake Mälaren, Sweden	0.015 ± 0.002	n.d.		0.02-0.05	0.009-0.013	0.008-0.047	1.52-2.84		(Strömbeck et al., 2001; Pierson et al., 2001)
Finnish lakes	0.015 ± 0.001	400-750							(Kallio et al., 2005)
Dutch Lakes	0.016 ± 0.002	350-750	0.013		0.009				(Rijkeboer et al., 1997)
Lake Taihu, China	0.011 ± 0.002	300-600	0.021		0.009-0.0129				(Zhang et al., 2007; Le et al., 2009)
Laguna Ibeña, Argentina	0.0115-0.0205	270-400							(Loiselle et al., 2009)
Lake Erie, North America			0.04	0.004-0.063					(Binding et al., 2008)
Nebraska, Iowa Lakes			0.005-0.050						(Dall'Olmo et al., 2005)
Lake Tianmuhu, China					0.0094-0.0123				(Zhang et al., 2009)
Lake Taupo, New Zealand					0.08 – 0.012		0.41-0.79		(Belzile et al., 2004)
Finnish and Estonian Lakes				0.01-0.09	0.006-0.0109		0.13-2.53		(Herlevi, 2002a; Paavel et al., 2007)
Cultured specimens								0.00001-0.001	(Ahn et al., 1992; Kutser et al., 2006; Metsamaa et al., 2006)

The direct comparison of phytoplankton absorption spectra is limited by the predominance of graphical rather than numerical reporting. The measured range of the specific phytoplankton absorption at the 670-676nm peak in the Queensland water bodies is comparable to measurements made for New Zealand freshwater (Davies-Colley et al., 1986; Belzile et al., 2004) and the mean measured values for Dutch lakes (Rijkeboer et al., 1997) and Lake Taihu (Le et al., 2009) but considerably lower than that measured for Lake Erie in North America (Binding et al., 2008). The measured values are within the range measured in a variety of lakes in Nebraska and Iowa (Dall'Olmo et al., 2005).

The measured range of the spectral slope of the specific tripton absorption for the Queensland water bodies bracket the values measured at Chinese lakes Taihu (Ma et al., 2006) and Tianmuhu (Zhang et al., 2009), Lake Taupo, New Zealand (Belzile et al., 2004), Finnish and Estonian Lakes (Paavel et al., 2007), Lake Mälaren, Sweden (Pierson et al., 2001) and the mean measured values for Dutch lakes (Rijkeboer et al., 1997). The values of $a_{TR}^*(550)$ are predominately within the range of values reported for Lake Erie (Binding et al., 2008) and the Nordic lakes (Pierson et al., 2001; Paavel et al., 2007) (the published a_{TR}^* values were transformed to $a_{TR}^*(550)$ using their quoted slopes).

Published values for the specific backscattering of tripton and phytoplankton are rare but once again by transforming the published $b_b^*(400)$ values to $b_b^*(542)$ using their published slopes, the Lake Mälaren measurements of Pierson and Strömbeck (2001) show similar values for $b_b^*(542)$. The range of spectral slopes measured for Wivenhoe Dam and Burdekin Falls Dam were lower than that measured in Lake Mälaren but they are comparable to values measured for Finnish and Estonian lakes (Herlevi, 2002a; Paavel et al., 2007) and Lake Taupo, New Zealand (Belzile et al., 2004).

The specific backscattering of phytoplankton at 620 nm values measured for Wivenhoe Dam were comparable to the values obtained for cultures by Ahn et al. (1992) and Vaillancourt et al. (2004) but exceeded the values reported by Kutser et al. (2006) and Metsamaa et al. (2006). The values for Burdekin Falls Dam were higher than these other

recorded values. The spectral slope of a power law model for the specific backscattering of phytoplankton has been shown to have a mean of $-1.4 \pm 0.5 \text{ nm}^{-1}$ (Vaillancourt et al., 2004) and the slope for cyanobacterial species has been shown to higher than phytoplankton species (Ahn et al., 1992; Metsamaa et al., 2006). The total backscattering slopes measured for the study sites fall within this range and the cyanobacteria dominated Burdekin Falls Dam samples show a greater slope, but the domination of backscattering by tripton means these spectra should be treated with caution.

Conclusion

This paper describes one partial and two complete Australian inland water SIOP sets to allow international and national comparison. In general terms there is little difference in the shape of the specific phytoplankton absorption spectra measured at different stations across Wivenhoe Dam but there was a significant difference between spectra measured across Burdekin Falls Dam. As might be expected there were differences between the spectra measured in the tropical and sub-tropical impoundments. The measured spectral slopes of the specific absorption of CDOM ranged from $0.0156 - 0.0190 \text{ nm}^{-1}$ and showed limited variation within and between impoundments. The measured spectral slopes of the specific absorption of tripton were similar in Wivenhoe and Fairbairn Dams with a range of $0.0080 - 0.0089 \text{ nm}^{-1}$ and showed limited variation within the water bodies. In contrast the specific absorption of tripton spectral slopes for Burdekin Falls Dam stations (range: $0.0123 - 0.0153 \text{ nm}^{-1}$) were larger and showed a greater variation within the impoundment. There was greater variation within and between the impoundments for the value on $a_{TR}^*(550)$ with ranges of $0.035 - 0.145 \text{ m}^2\text{g}^{-1}$ for Wivenhoe Dam, $0.014 - 0.022 \text{ m}^2\text{g}^{-1}$ for Burdekin Falls Dam and $0.034 - 0.038 \text{ m}^2\text{g}^{-1}$ for Fairbairn Dam. Among the eleven stations measured at Burdekin Falls Dam there was a greater spatial variation in the tripton backscattering spectral slope, $b_{bTR}^*(542)$ and the backscattering ratio values than Wivenhoe Dam. Both sites deviated from the conventional Petzold (1972) turbid water backscattering ratio (0.019) with Burdekin Falls Dam being higher (0.039-0.093) and Wivenhoe Dam being lower. The measured values were within the ranges of measured values in other environments and the difference is most likely due to the relative concentrations of phytoplankton and tripton (Kirk, 1994).

There was sufficient intra-impoundment variation in the specific absorption and specific scattering of phytoplankton and tripton to require a well distributed network of measurement stations to fully characterise the SIOPs of the optical water quality parameters. The variation in catchment conditions and impoundment morphology resulted in significantly different SIOP sets for each of the study sites. The significance of these variations on the accuracy and precision of optical water quality parameters has been estimated by simulation (Campbell et al., 2010; Campbell et al., 2009) but remains to be confirmed by application to satellite imagery.

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