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PRIMARY RESEARCH PAPER

# Unusual links between inherent and apparent optical properties in shallow lakes, the case of Taihu Lake

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**Abstract** The spectral distribution of downwelling solar irradiance is an important factor in the radiative balance, primary productivity and biogeochemistry in most lakes. In the present study, we show the relative importance of different inherent and apparent optical properties in controlling the spectral attenuation of diffuse downwelling irradiance in a large shallow lake in eastern China. Most importantly, we show how elevated concentrations of suspended matter not only increase attenuation, but are linked to a "spectral shift" in major attenuation peaks, with important consequences on biogeochemical processes and remote sensing. The analysis of the lake optical properties in relation to the geographical distribution of submerged macrophytes indicates how heterogenic optical conditions play a role in controlling benthic primary production.

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## Introduction

The spectral characteristics of the downwelling solar irradiance in aquatic ecosystems play a major role in ecosystem functioning and dynamics. The spectral distribution of availability solar irradiance influences the phytoplankton community structure and biodiversity in general (Stomp et al., 2007). Major biogeochemical processes (e.g., photodegradation of organic matter) are influenced by the depth to which solar irradiance, in particular ultraviolet radiation, penetrates into the water column (Bertilsson & Tranvik, 2007; Loiselle et al., 2009). The radiative balance between absorbed and reflected solar irradiance is strongly influenced by the spectral attenuation characteristics of surface waters.

The attenuation of diffuse downwelling solar irradiance is controlled by concentrations and optical properties of dissolved and particulate components in the water column, as well as by the angular distribution of the irradiance. The diffuse attenuation coefficient, $K_{d\lambda}$, quantifies the rate of change of solar irradiance with increasing depth in the euphotic zone. It is defined as the exponential decrease with depth of the ambient downwelling irradiance $E_{d\lambda}$, which comprises all photons moving in a downward direction (>90° with respect to the vertical) (Mobley, 1994):

$$E_{d\lambda}(z) = E_{o\lambda} \quad e^{-K_{d\lambda} z} \quad (\mathrm{W\,m^{-2}\,nm^{-1}}), \tag{1}$$

where $K_{d\lambda}$ is the diffuse attenuation coefficient ($m^{-1}$) at wavelength $\lambda$ (nm), $E_{d\lambda}$ is the downward irradiance (W $m^{-2}$ $nm^{-1}$) measured at depth $z$ (m) at wavelength $\lambda$ in a nonstratified water column, while $E_{o\lambda}$ is the downward irradiance just below the water surface. It should be noted that the estimation of $K_{d\lambda}$ is sensitive to the method used to fit the profile of decreasing irradiance with depth. Fitting nonlinear data, in this case an exponential decay, with linear fitting methods tends to distort the distribution of the data, as a transformation of the original data to linear form is necessary, in this case by converting exponential decay to linear decay using its natural log. By transforming the data, the distribution of points around the fitted line is modified, and the estimated $K_{d\lambda}$ and $E_{o\lambda}$ will be slightly different with that estimated using a nonlinear fitting approach. This can have important consequences when spectral distributions are compared.

By comparing the inherent optical properties of the aquatic medium (e.g., the absorption coefficients of the dissolved and particulate fractions) to the spectral distribution of the diffuse attenuation coefficient ($K_{d\lambda}$), insights can be gained as to which factors control solar irradiance at different wavelengths and in different areas of the aquatic ecosystem (Bukaveckas & Robbins-Forbes, 2000; Loiselle et al., 2008). Considerable research has been done to estimate $K_{d\lambda}$ for various types of water bodies using in situ as well as space-borne sensors (Lee et al., 2005; Pierson et al., 2008, Balogh et al., 2009). Classification schemes, ocean color remote sensing indexes and photodegradation studies—all use the relationship between spectral attenuation and the inherent optical properties of the dominant optical components to study temporal and spatial variations of the world's oceans and lakes, including the recent works by Boss et al. (2007) and Del Vecchio et al. (2009).

The understanding of the variability of $K_{d\lambda}$ is particularly important in shallow lakes (Zhang et al., 2007), where the euphotic depth may extend to the lake bottom, linking spatial changes in spectral attenuation to benthic productivity and macrophyte growth (Vermaat & Debruyne, 1993; Squires et al., 2002). In China, many of the most important and largest lakes are very shallow (Wang & Dou, 1998). These ecosystems are often found in heavily populated areas and play an important role in the regional water supply. However, economic and demographic growth have led to massive changes in the watershed of many of these lakes, resulting in major modifications in their optical and biogeochemical characteristics (Sun et al., 2010). It is fundamental to get a more complete understanding of the factors that control the spatial and temporal heterogeneity of these lakes (Duan et al., 2009). This heterogeneity is strongly influenced by the relationship between the concentrations of the attenuating components in the water column and lake depth. Changes in attenuation will strongly influence lake dynamics, including primary production in both the water column and at the sediment surface.

In the present study, we explore the role of inherent and apparent optical properties in controlling $K_{d\lambda}$ in one of the most important large lakes in China, Taihu Lake. We examine the relative importance of each optically active component in the total variance of $K_{d\lambda}$ and show how spatially heterogeneous optical conditions have potential impacts on phytoplankton production and submerged macrophyte distribution. Finally, we show how elevated particulate concentrations can modify spectral attenuation maxima, with important consequences to the spectral distribution of solar irradiance throughout the water column.

## Methods

Taihu Lake is a typical shallow lake in the Yangtze River Delta on the border of the Jiangsu and Zhejiang provinces in China. With an area of 2,338 $km^2$ and a mean depth of 1.9 m, it is the third largest freshwater lake in China (Qin, 2008). Limited depth and long fetch create conditions where suspended sediments play an important role in the optical and nutrient regimes of the lake. Eutrophication and recurrent algal blooms, often dominated by *Microcystis* spp., are a significant threat to the millions who rely on this lake as water supply (Guo, 2007). From 1987 to 2007, the annual duration of algal blooms increased, occurring first in the northern bays closest to the major population areas (Duan et al., 2009). Recent studies (Paerl et al., 2010) have indicated that nutrient loads from the heavily populated catchment play an important role in the eutrophication of the northern bays of the lake.

In the present study, a large number of sites (100; Fig. 1) were selected to examine the optical properties throughout the lake, the role of optically active components in controlling the spectral attenuation of solar irradiance in the water column and the potential role of the underwater light field on lake dynamics. The measurements were made over 11 days in October 2008.

Profiles of downwelling irradiance were made using a TriOS spectroradiometer. Measurements were made every 0.30 m down to the lake bottom, usually at five depths (0.30, 0.60, 0.90, 1.20, and 1.50 m) from the sunny side of the boat, under constant sky conditions and with wind speeds <2 m $s^{-1}$. Five parallel spectral readings were taken at each depth. Wavelength and energy calibrations with a step of 3 nm between 350 and 950 nm (Froidefond & Ouillon, 2005) were performed prior to measurements at each site. During immersion, data from the TriOS system were logged and processed using the manufacturer's offsets and calibration coefficients. We used the immersion calibration provided by the manufacturer in December 2007, so no correction factors were necessary (Ohde & Siegel, 2003). All

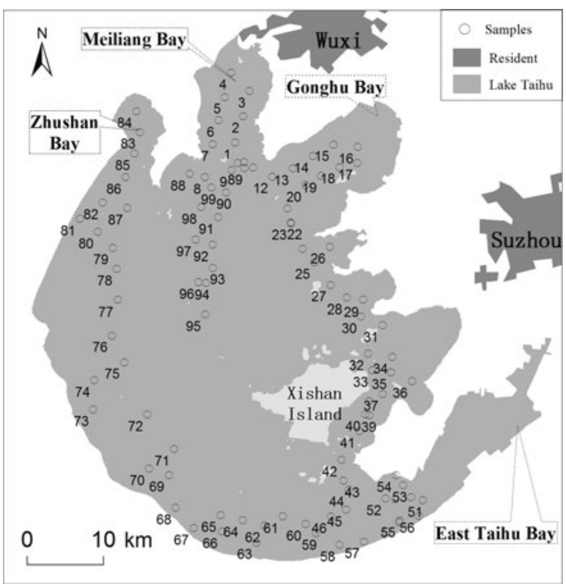


**Fig. 1** Sampling sites during the October 2008 survey of Taihu Lake. Adjacent cities of Suzhou (population 1.7 million) and Wuxi (population 2.2 million) also shown

irradiance data with a signal-to-noise ratio of <10 were removed from the data set. The arithmetic average of the five parallel irradiance measurements from 350 to 802 nm was used to determine $K_{d\lambda}$ using a nonlinear fitting algorithm (Levenberg–Marquardt) within the Interactive Data Language program. This algorithm combines the steepest descent and inverse-Hessian function fitting methods to fit the least squares curve (Press et al., 1992). $K_{d\lambda}$, and $E_{d\lambda(z=0)}$ were calculated for each site, as well as the goodness-of-fit ($R^2$). All estimates with a fitting below $P = 0.001$ ($R^2 > 0.95$) were removed from the data set.

Water samples were collected from the surface to a depth of 0.30 m using pre-rinsed standard 2 l polyethylene bottles. The absorption by total suspended matter was determined using the quantitative filter technique (Yentsch, 1962). Particulate matter of a known volume was concentrated onto a 47 mm Whatman GF/F filter. Absorbance was measured using a Shimadzu UV2401 spectrophotometer (Shimadzu, Tokyo, Japan) at 1 nm intervals in the range of 400–750 nm. The filter was placed close to the detector/collimator (distance 2–3 mm) and no diffuser was used. The absorbance at 750 nm was subtracted to remove scattering, assuming that there should be minimum absorption at this wavelength (Twardowski et al., 1999). The resulting spectrum was subsequently corrected for path-length amplification by applying

$$A_s = 0.378A_f + 0.523A_f^2, \quad (2)$$

where $A_f$ (<0.4) is the absorbance before correction for path-length amplification (Cleveland & Weidemann, 1993). Absorption by total particulate matter ($a_{p\lambda}$, $m^{-1}$) was then calculated as

$$a_{p\lambda} = \frac{2.303 \cdot S \cdot A_s}{V}, \quad (3)$$

where $S$ ($m^2$) is the clearance area of the filtration manifold, $A_s$ is the corrected particulate absorbance, and $V$ ($m^3$) is the volume of water filtered.

For the determination of absorption of colored dissolved organic matter (CDOM), collected water was filtered through a Whatman GF/F filter, and then refiltered at 0.22 μm (Millex GP Filter Unit, Millipore S.A., Malsheim, France) to remove particles. Absorbance spectra between 280 and 700 nm were acquired using a Shimadzu UV2401 spectrophotometer. Reference scans for instrument noise and bi-distilled water were also made. Absorbance, $A_\lambda$, was converted to absorption, $a_\lambda$ ($m^{-1}$):

$$a_\lambda = \frac{2.303 \cdot A_\lambda}{r}, \quad (4)$$

where $r$ (m) is the pathlength in the cuvette. A baseline of the absorption at 700 nm was used to correct for scattering caused by fine particulates (Keith et al., 2002). Slope coefficients ($S$, $nm^{-1}$) of absorption spectra were estimated using a nonlinear fitting technique (Levenberg–Marquardt minimizing method, Loiselle et al., 2009) according to which:

$$a(\lambda) = a_o e^{S(\lambda_0 - \lambda)} + k, \quad (5)$$

where $a_o$ is the absorption coefficient at $\lambda_0$ (e.g., 280 nm), and $k$ is a background parameter near zero, included to examine the goodness of the exponential fit. Spectral slopes were calculated over the spectral region from 280 to 300 nm ($S_{280-300}$), as this slope interval has proven to be sensitive to photoinduced changes in CDOM optical properties. Spectral slope intervals that extend into the visible wavelengths have been shown to provide little additional information for separating CDOM characteristics (Galgani et al., 2010). Correlation coefficients between the estimated exponential curve and the measured absorption were found to be >0.99.

Total suspended particulate matter (TSM) was determined gravimetrically from samples collected on pre-combusted and pre-weighed GF/F filters with a diameter of 47 mm, dried at 95°C overnight.

The concentration of chlorophyll *a* (Chl-*a*) was determined spectrophotometrically after first filtering the algae on a Whatman GF/F glass fiber filters, and then soaking it in 90% ethanol in the dark for 4–6 h. Samples were then heated to 80–90°C for 3–5 min. Absorbance of the extract was measured using a Shimadzu UV2401 spectrophotometer and concentrations determined following standard methods (Strickland & Parsons, 1972). The concentration of phycocyanin was determined after extraction with 0.05 M pH 7.0 Tris buffer and using a Shimadzu UV2450 spectrofluorophotometer at an excitation wavelength of 620 nm and an emission wavelength of 647 nm (Abalde et al., 1998; Yan et al., 2004).

The relative importance of CDOM absorption and particulate absorption in the variance in $K_{d\lambda}$ was determined by comparing absorption and attenuation for the full data set and determining the coefficient of determination ($R^2$) at each wavelength. For example, the CDOM absorption data set was compared to the corresponding $K_{d\lambda}$ data set to determine the relative importance of the $a_{CDOM\lambda}$ in the variability of the $K_{d\lambda}$, at each wavelength. The same was done with the $a_{p\lambda}$ data set to determine the relative importance of particulate related absorption.

### Regional analysis of apparent optical properties

A spatial analysis of the lake was made based on the site specific estimates of the apparent optical properties and using a spatial interpolation method (kriging). The method considers not only the distance between sampling sites, but also the spatial distribution of sampling points based on the analysis of variance and the structure function theory. Maps were generated (ESRI ArcMap 9.3) using an ordinary kriging approach, which assumes a constant but unknown mean, to divide the lake into optically similar areas.

## Results

Of the 100 irradiance profiles, 88 spectral attenuation curves (318–802 nm) were determined with a $R^2 > 0.95$ ($P < 0.01$). The spectral diffuse attenuation coefficients ($K_{d\lambda}$) showed a distribution typical of turbid waters (Fig. 1), at all sites. Most sites showed two major peaks, the largest centered in the ultraviolet A waveband (320–400 nm, UVA) and a second peak in the near infrared waveband (700–1400 nm, NIR). Two smaller peaks, one around 620 nm and the other near 680 nm, were also present at many sites. To illustrate the range of values, three sites were chosen: site 32 with a spectral attenuation at 500 nm close to the average of all 88 sites, site 12 with a higher attenuation (one standard deviation larger at 500 nm) and site 78, which was characterized by lower attenuation coefficients (about one standard deviation smaller at 500 nm). The three sites are representative of the west, north, and east parts of the lake, respectively (Fig. 2).

Optical properties showed a wide variation between sites (Table 1). CDOM absorption followed the expected exponential decay at all sites, with a high absorption in the ultraviolet wavelengths and a low absorption in the larger visible wavelengths (Fig. 3a). CDOM absorption was typical for a

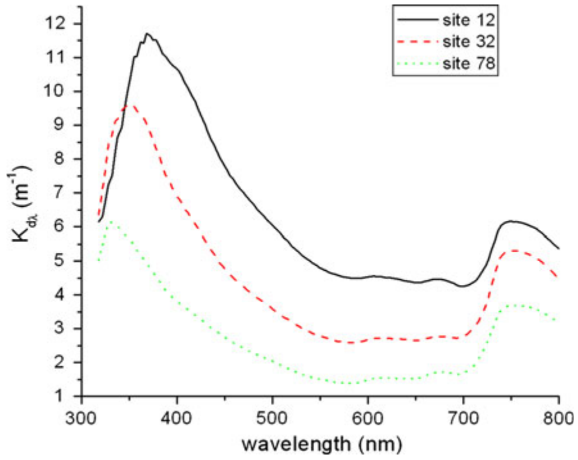


**Fig. 2** The spectral distribution of $K_{d\lambda}$ for three sites in Lake Taihu chosen to represent average attenuation (Site 32), high attenuation (Site 12, +1 standard deviation at 500 nm) and low attenuation (Site 78, −1 standard deviation at 500 nm). Sampling site numbers correspond to those in Fig. 1

**Table 1** Optical, chemical, and physical characteristics of Taihu Lake in October 2008

| | Mean | SD | Median |
|---|---|---|---|
| Lake depth (m) | 2.46 | 0.37 | 2.50 |
| Chl-*a* (mg m$^{-3}$) | 24.78 | 30.85 | 17.16 |
| Phycocyanin (mg m$^{-3}$) | 2.02 | 2.19 | 1.61 |
| TSM (g m$^{-3}$) | 28.40 | 23.70 | 24.83 |
| $a_{p465}$ (m$^{-1}$) | 1.59 | 1.15 | 1.39 |
| $a_{CDOM365}$ (m$^{-1}$) | 2.45 | 0.77 | 2.25 |
| CDOM slope$_{280–300\ nm}$ (nm$^{-1}$) | −0.023 | 0.002 | −0.023 |
| Secchi depth (m) | 0.57 | 0.43 | 0.40 |

eutrophic shallow lake with a moderate humic matter content. Also the absorption by total particulate matter ($a_{p\lambda}$) showed a nearly exponential decrease from ultraviolet to visible wavelengths with small peaks around 620 and 680 nm.

The relative importance of CDOM absorption and particulate absorption in the variance in $K_{d\lambda}$ indicated that $a_{CDOM\lambda}$ reaches a maximum at 365 nm, where it explains 25% of the total variance in $K_{d\lambda}$ (Fig. 4). The importance of $a_{CDOM\lambda}$ in $K_{d\lambda}$ is no longer significant ($P = 0.01$) after 465 nm. The importance of $a_{p\lambda}$ in $K_{d\lambda}$ is highest in the ultraviolet wavelengths, and remains significant throughout the visible wavelengths until 750 nm.

A spatial interpolation method was used to optically regionalize the lake based on the $K_{d\lambda}$ values

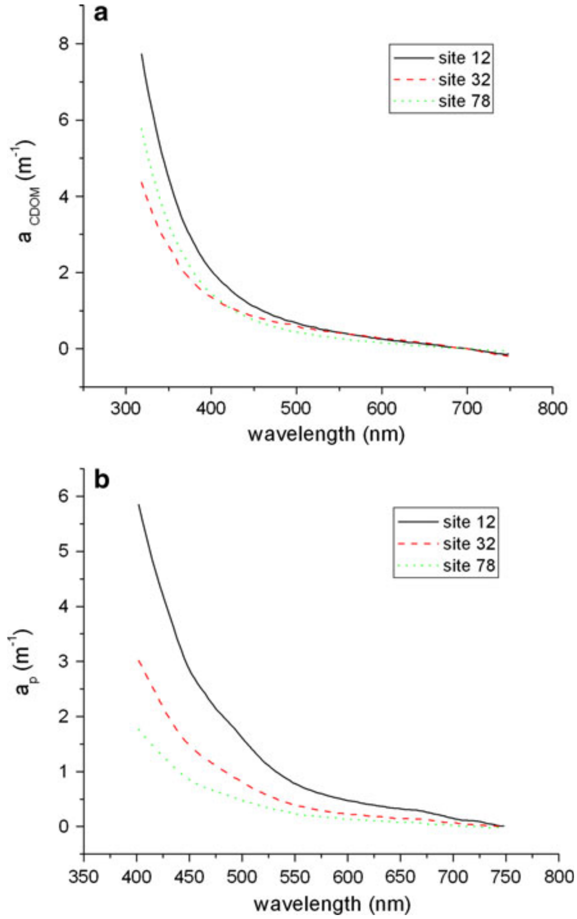


**Fig. 3** Spectral distributions of inherent optical properties at three sites of Lake Taihu in October 2008, **a** CDOM absorption (m$^{-1}$) and **b** particulate absorption (m$^{-1}$)

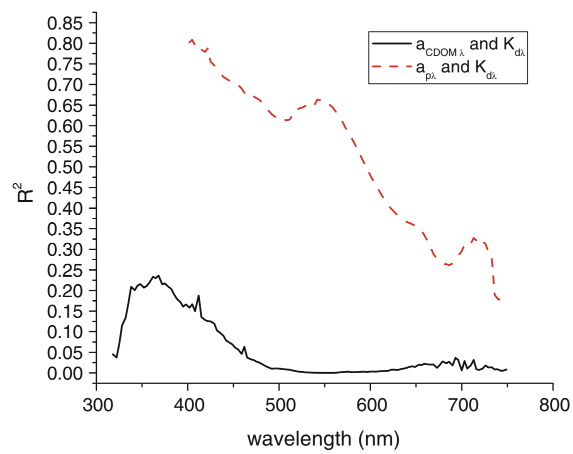


**Fig. 4** The proportion of $K_{d\lambda}$ variance explained by CDOM and particulate matter absorption, found as the spectral variation of the determination coefficient ($R^2$)

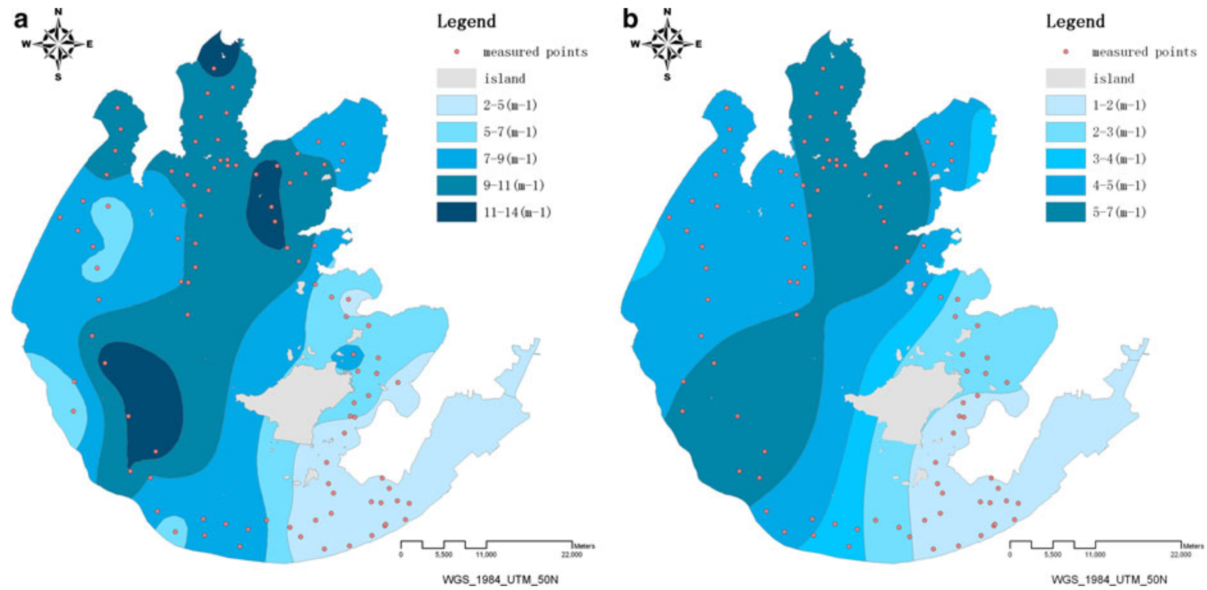


**Fig. 5** Geographic differences in the spectral attenuation coefficient at two wavelengths **a** $K_{d365}$ and **b** $K_{d465}$. Sampling sites are indicated by *circles*. As measurements were impossible in the shallow bay in the southeast part of the lake, the estimated attenuation coefficients for this area should not be considered

(Fig. 5). The distribution of the diffuse attenuation coefficient at 365 nm ($K_{d365}$) showed maxima in the northern bays nearest to the population centers (Meiliang and Gonghu Bays) and in the southwestern part of the lake, indicating areas where high dissolved and particulate organic matter may be present. $K_{d465}$, often associated with attenuation due to both phytoplankton and organic matter, was highest in the central part of the lake, stretching from Gonghu Bay to the southwestern coast. In general, the lake could be divided into four regions: the central region, extending from north to south characterized by high attenuation at all wavelengths, two bordering regions that reach the coast in the west and the islands to the east, and an eastern region with very low attenuation. Attenuation decreases by a factor of 4–5 from the central area to the eastern area of the lake. It should be noted that due to the presence of submerged macrophytes, it was not possible to measure vertical irradiance profiles in the East Taihu Bay (southeastern part of the lake) and therefore values given by interpolation should not be considered.

At first glance, there is little variability in the shape of the $K_{d\lambda}$ spectral distribution in the Taihu Lake data set. Two major peaks (Fig. 2), generally associated with absorption by organic matter (in the UVA) and absorption from water (in the NIR) occur throughout. At many sites, two minor peaks are present near 620 and 680 nm. However, taking a closer look at the wavelengths in which these peaks occur, an interesting "spectral shift" can be observed. For example, the attenuation peak in the UVA tends to "red shift" to higher wavelengths when overall attenuation is high (e.g., Fig. 2). This shift in the UVA attenuation peak may be significant, ranging from 330 to 380 nm. The attenuation maximum in the UVA is the result of absorption by organic matter, absorption by water, and absorption by particulates (Fig. 4).

In the present data set, a positive correlation between TSM concentrations and the wavelength of the $K_{d\lambda}$ peak in UVA was seen ($R^2 = 0.77$, Fig. 6a). In the same manner, the peak of minimum attenuation (573–593 nm) was seen to show a significant red shift over a smaller wavelength range. This red shift showed a clear correlation to particulate concentrations ($R^2 = 0.70$) (Fig. 6b).

## Discussion

### Influence of optically active components on $K_{d\lambda}$

In all aquatic systems, spectral attenuation is strongly influenced by the concentration and spectral

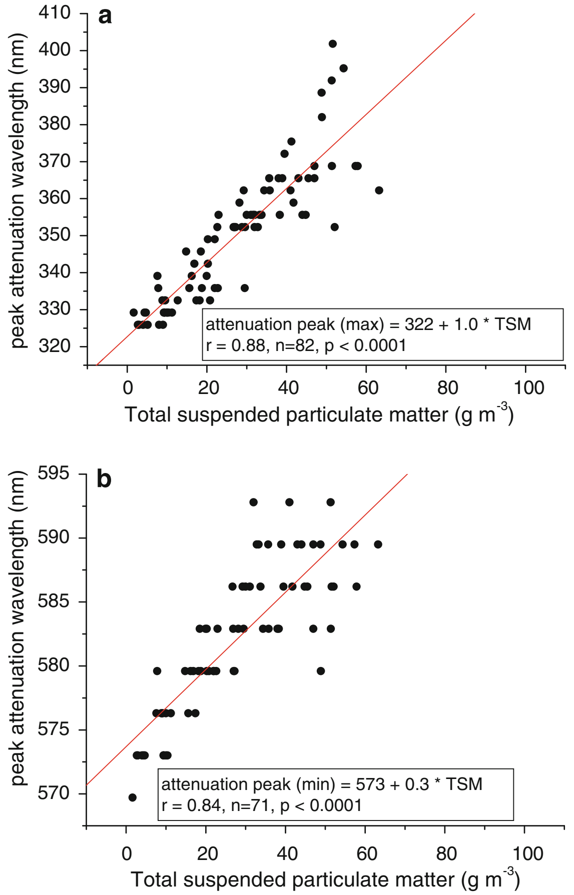


**Fig. 6** Correlations between total suspended matter (TSM) and the wavelength of maximum attenuation in the UVA wavelengths (**a**) and minimum attenuation in the mid-visible wavelengths (**b**)

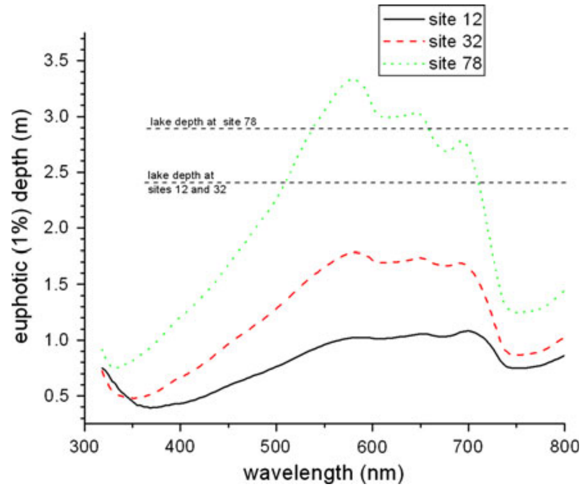


**Fig. 7** Euphotic depth (1% of downwelling solar irradiance just below the surface) and lake depth at three sites in Taihu Lake

characteristics of the dissolved and particulate matter present. In the turbid waters of Taihu Lake, particulate matter plays a dominant role in the attenuation of the incident solar irradiance. The relative dominance of particulate-related absorption extends throughout the visible wavelengths and into the near infrared, where absorption of water also becomes relevant (Morel & Prieur, 1977; Smith & Baker, 1978). It should be noted that the correlations described are based on a linear relationship between variables.

The spectral distribution of $a_{p\lambda}$ showed the presence of two small peaks in absorption occurring near 620 and 680 nm. By isolating these peaks and comparing them with the measured concentrations of phycocyanin and chlorophyll *a*, Simis et al. (2005) found strong positive and significant correlations between the $a_{p619}$ and phycocyanin concentrations ($R^2 = 0.56$, $P < 0.001$), and $a_{p680}$ and chlorophyll concentrations ($R^2 = 0.91$, $P < 0.001$).

## Spectral shifts in $K_{d\lambda}$

In general, $a_{CDOM\lambda}$ (and $a_{p\lambda}$) have a rapid and constant decrease in spectral absorption throughout the UVA/visible wavelengths. In waters with low particulate concentrations, absorption dominates the vertical attenuation, pushing the attenuation peak to lower wavelengths. The increasing particulate concentrations in turbid waters have both direct and indirect effects on attenuation. Indirect effects (increased scattering) results in the flattening of the angular distribution of the downwelling radiance (Sullivan & Twardowski, 2009). The reduced vertical path of the downwelling photons tends to increase attenuation but also shifts the peak attenuation toward wavelengths where photon density is higher. This was verified by comparing particulate concentrations to the position (wavelength) of the $K_{d\lambda}$ peaks (Fig. 6). The positive and highly significant correlation indicates that a shift in the attenuation peak to higher wavelengths occurred at sites with elevated concentrations of particulate matter. This was seen for both the attenuation maximum in the UV waveband and the attenuation minimum observed in the mid-visible wavelengths (573–593 nm). However, the attenuation peaks expected at 620 and 680 nm were found to be shifted toward lower wavelengths at high particulate concentrations. This "blue shift" occurred over a small wavelength interval, 610–641 nm and 663–692 nm, but was significantly correlated to particulate concentrations for both attenuation peaks ($R^2 = 0.50$, $R^2 = 0.52$ for the expected peaks at 620 and 680 nm, respectively).

Major shifts in attenuation peaks to higher wavelengths in the ultraviolet and visible wavelengths have been shown to affect phytoplankton composition as well as leading to photoacclimation (Dubinsky & Stambler, 2009). On the other hand, blue-shifted peaks at higher wavelengths will modify the spectral distribution of the water leaving radiance, as upwelling irradiance is strongly linked to the attenuation of the downwelling irradiance. This could have important consequences for the remote monitoring of phytoplankton biomass. Red shifts in the upwelling maxima have been reported for turbid waters (Topliss, 1986), but shifts in both directions have not been reported yet. The wide range of optical conditions in Taihu Lake made it possible to observe these unusual changes in spectral attenuation.

## Impacts on light penetration

Variability in the spectral attenuation creates conditions where the euphotic depth, $z_{\text{euphotic }\lambda} = \ln(0.01)/K_{\text{d}\lambda}$, and the resulting spectral distribution of solar irradiance on the lake bottom are spatially heterogeneous. For example, the euphotic depth at site 12, reaches a maximum of one meter at the mid- to far-visible wavelengths (Fig. 7). The lake depth at this site is nearly 2.5 m. As the water column did not show a thermal stratification, the euphotic depth is smaller than the mixing depth and lake depth at this site. Such conditions indicate the possibility for light limitation of phytoplankton growth, as circulating phytoplankton cells will move in and out of the euphotic zone (Le et al., 2009). Site 32 located in the eastern part of the lake shows a similar case. The highest euphotic depth (at 580 nm) was found to be near 1.8 m, close to, but still less than the lake depth of 2.5 m at this site. On the other hand, the spectral distribution of the downwelling irradiance at site 78, located on the western part of the lake, shows that more than 1% of the subsurface solar irradiance between 540 and 660 nm is expected to reach the lake bottom. It should be noted that light limitation for phytoplankton organisms will also strongly depend on their buoyant velocity together with the turbulent mixing caused by wind stress and local conditions (e.g., presence of macrophytes, Visser et al., 1996). Cyanobacteria, one of the dominant groups of phytoplankton in the lake (Duan et al., 2009) are evidenced by peaks in absorption and attenuation around 620 nm. The vertical distribution of phytoplankton needs to be considered before light limitation of phytoplankton productivity can be hypothesized. The vertical resolution of the irradiance profiles in the present data set did not allow for the identification of gradients in $K_{\text{d}\lambda}$ with depth.

In addition to phytoplankton, benthic primary production will also be influenced by the relationship between euphotic depth and lake depth. Regarding solar UVA irradiance, none of the 88 sites analyzed showed more than 1% of the subsurface $E_{\text{dUVA}(z=0)}$ at the lake bottom. On the other hand, large areas of the lake bottom received more than 1% of $E_{\text{d}\lambda(z=0)}$ in the visible wavelengths (e.g., 675 nm, Fig. 8). As a result, a clear division of the lake can be made into areas where benthic primary productivity is possible and areas where solar irradiance does not reach the lake bottom. This distribution of available irradiance on the lake bottom was compared with the spatial distribution of submerged macrophytes determined in a previous survey (Fig. 9). A good correspondence

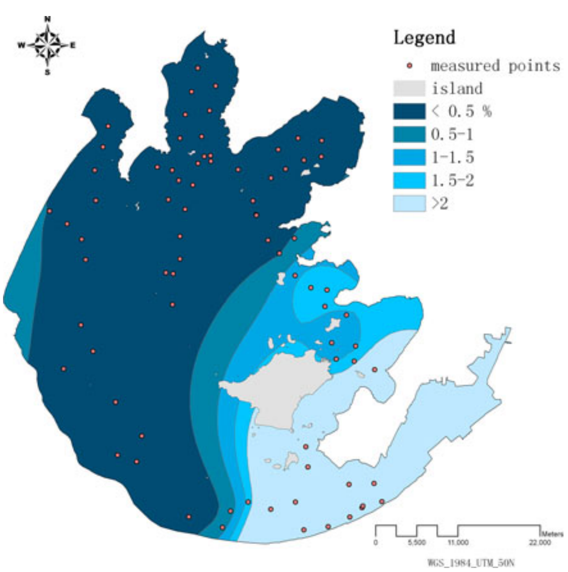


**Fig. 8** Light conditions in Taihu Lake, the percentage of subsurface downwelling diffuse solar irradiance at 676 nm reaching the lake bottom

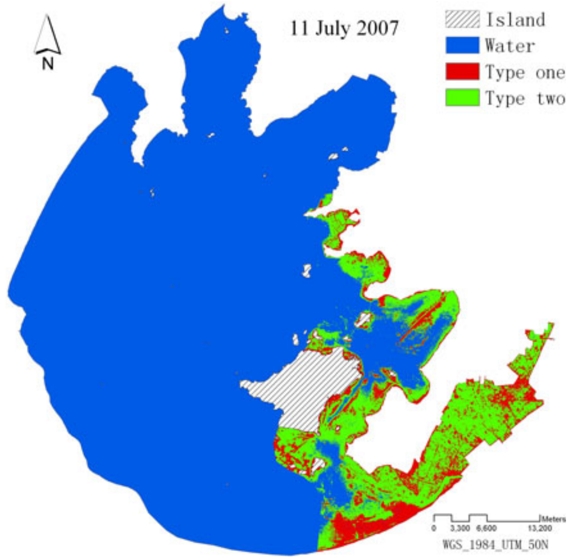


**Fig. 9** The spatial distribution of submerged (Type two, *Potamogeton malaianus* Miq. dominated) and floating-leaved (Type one, *Nymphoides peltatum* (Gmel.) O.Kuntze dominated) aquatic vegetation in Taihu Lake in June 2007 according to the classification approach described in Ma et al. (2008)

between areas colonized by submerged macrophytes and areas, where the euphotic depth is greater than lake depth was observed.

In recent years, the areas where submerged macrophytes are present have undergone large scale changes (Ma et al., 2008). From our analysis, it would appear that optical conditions (light limitation of benthic primary production) may influence these spatial dynamics. As the dominant optically active component of the water column, a reduction in the concentrations of particulates will favor further colonization by submerged macrophytes. Increases in macrophyte coverage would create a positive feedback, increasing sedimentation rates, further reducing attenuation, and increasing the available solar irradiance at the lake floor.

## Conclusions

The concentrations of total particulate matter dominate the attenuation of solar irradiance in Taihu Lake. Furthermore, these elevated particulate concentrations were also found to influence the spectral distribution of the vertical attenuation coefficient, leading to spectral shifts in attenuation maxima. These shifts in attenuation maxima can have unexpected consequences on the spectral distribution of solar irradiance throughout the water column.

In the ongoing management of water quality and ecosystem dynamics in Taihu Lake, the spatial and spectral distributions of the vertical attenuation coefficient are key variables to monitor. The spatial distribution of vertical attenuation can be estimated using satellite-based sensors. However, the variability in the spectral distribution of vertical attenuation requires extensive in situ irradiance data. The spectral shifts observed in the present study provide new insights into the role of particulate matter in modifying optical conditions in aquatic ecosystems, in particular in waters with a high particulate load, such as shallow lakes, rivers, and estuaries.

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