Light attenuation parameters for waste stabilisation ponds

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Abstract Effective modelling of shallow water ecosystems, including waste stabilisation ponds, is strongly dependent on the availability of good estimates of the light attenuation coefficient $k$ ($m^{-1}$). Experimental data is presented on its determination using purpose-built laboratory apparatus with a near-parallel halogen light source and an array of photodiodes allowing measurements of irradiance at different depths. The equipment was used to compare $k$ values from 4 different pure cultures, and mixed cultures of algae taken from a pilot-scale WSP. Laboratory values were compared with in situ measurements in the pond. At concentrations above 50 mg l$^{-1}$ the relationship between $k$ and suspended solids is non-linear; $k$ also varied with depth. This could be modelled by a single equation, suggesting similarity of response in different cultures. At shallow depths and low suspended solids concentrations $k$ values are variable and hard to measure reliably. The results highlight the need to standardise on a method for the measurement and reporting of $k$ values if these are to be widely applicable in the development of pond models.

Keywords Extinction coefficient; light attenuation; waste stabilisation ponds

Introduction Light plays a vital role in the functioning of a waste stabilisation pond (WSP), providing the energy source for photosynthesis and thus oxygen production. Knowledge of the parameters affecting light intensity or irradiance within the pond is thus crucial to modelling and prediction of WSP behaviour. There is an extensive scientific literature, both theoretical and experimental, on light attenuation in oceans and freshwater bodies, and also in photobioreactors. WSPs fall between these two applications, however, and relevant parameter values can be more difficult to find.

Attenuation of light follows an exponential relationship of the form

$$I_z = I_0 e^{-kz}$$

where $I_0$ is the subsurface irradiance, $I_z$ the irradiance at depth $z$ and $k$ is a light attenuation coefficient. A huge body of work in the fields of limnology and oceanography concerns values and expressions for $k$ (see Kirk, 1994). For many purposes $k$ is assumed to be a linear function of one or more components such as suspended solids (SS), dissolved solids or chlorophyll. Numerous expressions have been proposed for conditions similar to those in WSPs, such as eutrophic lakes and estuaries (e.g. Tsirtsis, 1995; Lonin and Tuchkovenko, 2001). Values of $k$ in excess of 10 m$^{-1}$ are quoted by Wetzel (2001) for stained and eutrophic lakes. Brawley et al. (2003) note that effective modelling of shallow water ecosystems is strongly dependent on the availability of good estimates for $k$.

Photobioreactors are designed to operate at concentrations of algal biomass far higher than those usually found in WSPs. In these conditions the assumption of linear dependence of $k$ on biomass concentration is known to be invalid. Yun and Park (2001) tried a theoretically based approach to modelling $k$ for Chlorella vulgaris in the biomass
concentration range 0–2000 mg l\(^{-1}\), using a linear approximation, an equation proposed by Cornet et al. (1992), and a hyperbolic model. While Cornet’s equation was more satisfactory in the sense of having a physical basis, the hyperbolic model was found to give the best fit. Fernandez et al. (1997) also found a hyperbolic model gave the best results for data from *Phaeodactylum tricornutum* at concentrations of up to 3000 mg l\(^{-1}\). At low biomass concentrations the effect of scattering was significant: for the range observed the highest value of \(k\) was found at 24 mg l\(^{-1}\), while 40–294 mg l\(^{-1}\) the relationship between \(k\) and biomass concentration appeared linear. Privoznik and Incropera (1978) also noted the relative importance of scattering in cultures of *Chlorella pyrenoidosa* at low concentrations. Ogbunna et al. (1995) calculated a specific \(k\) value per kg m\(^{-3}\) of 200 m\(^2\) kg\(^{-1}\) for *C. pyrenoidosa*, and applied this to modelling growth curves the range 17–3000 mg l\(^{-1}\).

A definitive study of light penetration in WSPs, looking at both photosynthetically active radiation (PAR) and monochromatic light, was carried out by Curtis et al. (1994). Absorbance played a far more important role than scattering for all ponds in the study, pond-to-pond variation was mainly attributable to differences in algal biomass, and variations in attenuation were observed at different wavelengths and depths. Despite this, in practice many models are based on simple empirical linear relationships, and measured absolute values for \(k\) are hard to find. Bartsch (1961) found \(k\) values of 6–11 m\(^{-1}\) in Dakota WSPs in summer, while Thomann and Mueller (1987) gives a value of 23 m\(^{-1}\). Mesplé et al. (1994) obtained a specific \(k\) value for total SS minus phytoplankton of 0.05 m\(^2\) per mg dry weight l\(^{-1}\), for high rate algal ponds. Juanico et al. (2003) used a specific \(k\) value of 0.29 m\(^{-1}\) per mg l\(^{-1}\) of carbon, based on literature values, and found that a change in light absorption and self-shading factors produced a two-fold change in average irradiance in spring, but was not significant in summer due to higher concentrations of algae and organic matter. A survey of WSPs in New Zealand found a median euphotic depth of 0.35 m corresponding to a \(k\) value of 13 m\(^{-1}\) (Davies-Colley et al., 1995).

In the current work, \(k\) values for mixed and pure cultures were measured in purpose-built laboratory apparatus, and also in three pilot-scale pond systems. As photosynthetic sulphate-reducing bacteria can also be present in pond systems in certain conditions, imparting a red-purple colour to the water, a mixed culture rich in these was also grown and tested.

**Materials and methods**

**Light sensors.** Light intensity was measured using type BPW 21 photodiodes (RS components, UK), used in similar applications elsewhere for measurement of PAR (Ensminger et al., 2001). Photodiodes for laboratory use were calibrated against a LI-210SA photometric sensor (LiCor, USA), while those used for external measurements were calibrated against a RC/0308 standard photovoltaic cell (PV Systems, UK). Where several photodiodes were to be used in one set of measurements, the output from each was checked against the average output from all under different conditions of illumination. A strong linear relationship \((R^2 > 0.998)\) was found, allowing calculation of a normalising factor. Photodiode outputs were continuously sampled using a datalogger (DataTaker DS500 and expansion unit). Readings were averaged over a 30 second period and then over longer periods as required. Output was measured in milliamps unless noted.

**Waste stabilisation ponds.** Measurements were made in three sets of pilot-scale ponds, two located in Almaty, Kazakhstan and one in Southampton, UK. The first set of Almaty ponds A(I) consisted of four circular concrete tanks 2 m in diameter with a water column depth of 1.5 m. The ponds were fed on screened wastewater from Almaty sewage works, with a typical 5-day biochemical oxygen demand (BODs) of 200 mg l\(^{-1}\). They were batch
fed over a one-hour period each day, to give hydraulic retention times of 7.5, 15, 22.5 and 30 days. An array of photodiodes constructed to read at the surface and at depths of 0.3, 0.6, 0.9 and 1.2 m was moved between the ponds on a 3-day cycle. Readings taken in millivolts were averaged over a 15-minute period. Construction and operation of the second set of Almaty ponds A(II) is described elsewhere (Banks et al., 2002). These ponds were instrumented each with a single photodiode at a depth of 0.25 m, with readings averaged over a 15-minute period. The work in Southampton was carried out on two ponds (SP1 and SP2) each with a surface area of 0.9 m² and a water column depth of 0.6 m. The ponds consisted of semi-translucent polypropylene tanks externally insulated with 50 mm of polystyrene foam, preventing any light entering through the tank walls. They were housed in a south-facing greenhouse, and received supplemental lighting from an array of halogen floodlights capable of providing a surface illumination of 300 W m⁻². They were batch fed on a synthetic wastewater of the type used for Almaty A(II) ponds, at a hydraulic retention time of 22 days. The ponds were instrumented with photodiodes at depths of 0, 0.15, 0.33 and 0.53 m and in normal operation readings were averaged over 10-minute intervals. For detailed comparison with laboratory measurements an array of eight photodiodes at depths of 0 (two diodes), 0.09, 0.18, 0.27, 0.36, 0.45, and 0.54 m was used, with measurements averaged over 1-minute intervals. In all cases readings were taken immediately after cleaning of the photodiode surface.

**Microbial suspensions.** Mixed cultures were taken from the Southampton ponds at different seasons; and a culture dominated by purple sulphur bacteria was grown in shallow pond water covering a layer of sulphur-rich pond sediment. Cultures of *Scenedesmus subspicatus* (CCAP 276/20), *Chlorella vulgaris* (CCAP 276/20), *Chlamydomonas reinhardtii* (CCAP 11/32b), and *Microcystis aeruginosa* (CCAP 1450/16) were obtained from the Culture Collection of Algae and Protozoa, Dunstaffnage Marine Laboratory, UK. Cultures were grown on Jaworski’s medium (CCAP JM recipe), modified for *M. aeruginosa* by the addition of 1 ml l⁻¹ of trace element solution (Piennig et al., 1981). Cultures were activated by inoculation into 250 ml flasks containing 100 ml of medium, and incubating for 4–7 days at 20°C on an illuminated orbital shaker (Gallenkamp, UK). The contents of each 250 ml flask were then transferred to a 2 litre flask containing 1 litre of medium, and incubated under the same conditions for a further 4–7 days. Two 2 litre flasks were then used to inoculate a 20 litre glass container aerated by a filtered air supply and illuminated by an array of eight 35 W white fluorescent tubes at 18–22°C for a further 4–7 days.

**Light apparatus.** Light attenuation measurements were made in a purpose-built column apparatus consisting of a dark grey non-reflective PVC tube 150 mm in diameter and 1.5 m deep, fitted with a horizontal array of six photodiodes located centrally to minimise wall effects. The array could be moved vertically through the column of water and positioned at any depth. Illumination of the water column could be achieved using different light sources, but the source used in the current work was a PAR 36 light with a sealed beam 30 W halogen lamp (General Electric 4515). This allowed near-parallel light to be directed at the water surface. A mathematical correction for divergence is possible (Privoznik and Incropera, 1978) but as each bulb had slightly different characteristics in practice correction was made by measuring the light intensity in air, and deducting the resultant value or slope of the line from values measured in the algal cultures (Fernandez et al., 1997). Sedimentation of algae was prevented by recirculation at a pumping rate in excess of algal settling rate (Stutz-McDonald and Williamson, 1979).

**Sampling and analysis.** Suspended solids were measured by filtration of an appropriate volume through a pre-dried and weighed GFC filter (Whatman, UK), in accordance with the procedures in *Standard Methods for the Examination of Water and Wastewater* (1998). Chlorophyll was determined by filtering through a GFC filter (Whatman, UK).
previously dosed with 1 ml of a saturated solution of MgSO₄. Extraction was by grinding followed by treatment with acetone and centrifugation for 15 minutes at 3000 rpm. The resultant colour was measured at 664 and 665 nm using a Cecil Instruments spectrophotometer (3000 series). Absorbance was measured at 664 nm in a colorimeter (Camlab DREL/5). Samples were analysed in triplicate.

Data handling. At low to medium suspended solids concentrations, where the relationship appeared linear, \( k \) values were obtained by plotting \( \ln(I) \) against depth \( z \), with \( k \) as the gradient of a line fitted by the method of least squares. At higher concentrations where the non-linearity of the relationship between \( \ln(I) \) and \( z \) is apparent, local \( k_z \) values were calculated for a given depth using the formula \( k_z = \ln(I/I_o)/z \). For calculation of daily in-pond \( k \) values, measurements were rejected if the correlation coefficient for \( z \) and \( \ln(I) \) was \( R^2 < 0.98 \). Measurements taken in Kazakhstan were also discarded if the irradiance readings indicated passage of clouds during the measurement period. All data processing was carried out using Excel spreadsheet software (Microsoft Excel).

Results and discussion

Light column experiments

The results of more than 60 sets of light attenuation measurements in the column apparatus described above carried out with pure and mixed cultures at different dilutions indicated that repeatability and reliability of measurements was good. The difference between values of \( k \) obtained from separate runs for the same culture and dilution was usually less than 0.1 m⁻¹. At low to medium concentrations of SS, where the relationship between depth and the natural logarithm of irradiance can be considered as linear, correlation coefficients between \( z \) and \( \ln(I) \) were generally in excess of 0.995 and often of 0.999. The relationship between \( k \) values and SS concentrations obtained by dilution of a given culture was also strongly linear at low concentrations, with \( R^2 > 0.995 \). Gradients for \( k \) versus SS were generally in the range of 0.12–0.2 m⁻¹ per mg l⁻¹ of suspended solids. These values agree well with Bowen (2004), who suggested an average value for algal biomass of 0.17 and a range of 0.06–0.34 m⁻¹ mg⁻¹l, based on a value of 19 m⁻¹ mg⁻¹l for chlorophyll.

At higher concentrations the assumption of linearity no longer holds true, initially for the relationship between \( k \) and SS and then for depth and \( \ln(I) \). Once the latter relationship is non-linear, \( k \) values can no longer be obtained from the gradient of \( z \) versus \( \ln(I) \) and local values for \( k_z \) must be calculated. Figures 1 and 2 show the variation of \( k_z \) with suspended solids and with depth for a culture of \( S. subspicatus \). At concentrations below 50 mg l⁻¹, values of \( k_z \) are similar at all depths and the relationship between \( k_z \) and SS is close to linear (Figure 1). Above this concentration, linearity is lost and the overall shape of the curve can be approximated by a hyperbola, in accordance with the findings of other researchers (Fernandez et al., 1997; Yun and Park, 2001). Values for \( k_z \) at different depths also show increasing divergence, as described by Kirk (1994). This can be seen more clearly in Figure 2 where for SS concentrations of 10 and 20 mg l⁻¹ the shape of the curve is approximately linear, in accordance with the findings of other researchers (Fernandez et al., 1997; Yun and Park, 2001). Values for \( k_z \) at different depths also show increasing divergence, as described by Kirk (1994). This can be seen more clearly in Figure 2 where for SS concentrations of 10 and 20 mg l⁻¹ the relationship between \( k_z \) and SS is close to linear (Figure 1). Above this concentration, linearity is lost and the overall shape of the curve can be approximated by a hyperbola, in accordance with the findings of other researchers (Fernandez et al., 1997; Yun and Park, 2001). Values for \( k_z \) at different depths also show increasing divergence, as described by Kirk (1994). This can be seen more clearly in Figure 2 where for SS concentrations of 10 and 20 mg l⁻¹ the relationship between \( k_z \) and SS is close to linear (Figure 1). Above this concentration, linearity is lost and the overall shape of the curve can be approximated by a hyperbola, in accordance with the findings of other researchers (Fernandez et al., 1997; Yun and Park, 2001).

The results for \( S. subspicatus \), \( C. reinhardtii \), \( C. vulgaris \) and \( M. aeruginosa \) showed a similar pattern of variation of \( k_z \) with both depth and SS. Figure 3 shows the variation of \( k_z \) for \( C. vulgaris \) plotted as a 3D surface. The response surface for \( S. subspicatus \) can be modelled by an equation of the form

\[
k_z = 0.4 \times \text{(depth in metres)} + 0.0001 \times \text{(SS in mg l}\text{⁻¹})^2 - 0.2\text{(SS in mg l}\text{⁻¹})
\]
giving a correlation of $R^2 = 0.94$ with the experimental data. The same equation applied to results for C. reinhardtii, C. vulgaris and M. aeruginosa gives $R^2 = 0.88$, 0.95 and 0.84 respectively, indicating good similarity. The lower value for M. aeruginosa may be due in part to the lower SS concentration in the experiment, and the low chlorophyll content of 0.04 mg l$^{-1}$ or 0.001 mg mg$^{-1}$. While equation (2) has no physical basis it does indicate that at depths typical for a WSP a linear correction for $k$ may be satisfactory, but variations with respect to SS are significant in the range of concentrations likely to be encountered. Figure 4 shows $k_z$ values for a mixed culture dominated by purple sulphur bacteria, with a high suspended solids content. The correlation coefficient for experimental and modelled data with the above expression was $R^2 = 0.94$.

Values of $k$ and $k_z$ were determined for mixed cultures from SP1 and SP2 in the concentration range 5–58 mg l$^{-1}$ SS. In the region of assumed linearity, $k$ values ranged from 5.2 to 14.7 m$^{-1}$. The results were compared with values measured in situ in SP1 and SP2 using an array of eight sensors. At SS concentrations above 25 mg l$^{-1}$, values...
measured by the two methods showed reasonably good agreement. The main difficulty was in obtaining reliable and reproducible $k$ values from measurements in the pond: accuracy requires bright sunlight, high solar elevation, a cloud-free sky, the absence of local shading, and minimal depth variations, as noted by Curtis et al. (1994). Results vary depending on whether the light is bright or diffused. Kirk (1994) note that $k$ may decrease with depth in diffuse light. While the photodiode array proved highly effective, optimum measurement conditions are often difficult to achieve in practice, providing an argument in support of laboratory-based methods. Values for $k$ and $k_z$ at SS concentrations below 20 mg l$^{-1}$ were more difficult to measure in either the ponds or the column apparatus, especially at shallow depths (up to 0.2 m). In the column apparatus, this could be due in part to limitations of the equipment: at very low concentrations of suspended solids little absorption takes place, scattering plays a greater role and edge effects from the column walls may become apparent. At shallow depths small errors in depth measurement also have a greater effect. On dilution of a given culture from 25 mg l$^{-1}$ to 10 and then 5 mg l$^{-1}$, however, the

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**Figure 3** Variation of $k_z$ with depth and SS for *C. vulgaris*  
**Figure 4** Variation of $k_z$ with depth and SS for mixed culture with purple sulphur bacteria
non-linearity of the relationship between $k$ and SS was clearly seen. Further support for the degree of variation in $k$ values at shallow depths can be found from several sources. Curtis et al. (1994) noted that rates of attenuation were sometimes lower near the surface. The results in Figure 2 suggest that $k$ values at shallow depth may be lower even at relatively high SS concentrations. In-pond measurements at shallow depth where wall effects are absent also showed a similar pattern of variation. This type of near-surface variation may cause problems for WSP modelling since under normal conditions the majority of photosynthetic activity occurs in the upper 0.2–0.3 metres, and values of $k$ or $k_z$ obtained over a greater depth may therefore not be applicable. The difficulty is compounded at low SS concentrations. This is not generally an issue in operational WSPs with steady-state SS concentrations of 30–100 mg l$^{-1}$, but may present problems in modelling pond start-up or for non-steady-state conditions such as those encountered in extreme climates.

There is clearly a need for standardisation in reporting of $k$ values in ponds. In photobioreactors operating at high SS concentrations attenuation constants are frequently reported as specific values in m$^2$ kg$^{-1}$ and may be based on a particular light path length, giving a value of $k_z$; while limnologists tend to measure over a long path length and assume linearity of $k$ with SS. Algal WSPs fall between these two applications, but in a range where linearity cannot be assumed and it may be necessary to specify depth, SS concentration and possibly even surface irradiance when reporting $k$ values.

**Pond measurements**

While the above discussion indicates some of the difficulties in measuring and calculating attenuation coefficients in WSPs, it was considered useful to have an idea of the range of values that might be expected under varying operating conditions. For this reason measurements were made in pilot-scale ponds in three locations as described above.

Values of $k$ for the Southampton ponds were in the range 4.8–13.7 m$^{-1}$ throughout a one-year period of observation, while suspended solids were in the range 42–172 mg l$^{-1}$. As the ponds were kept under semi-controlled conditions of light and temperature, and were subject to different experimental conditions in different periods, no clear seasonal trends were noted. There was a reasonable correlation between $k$ values and suspended solids concentrations in both ponds throughout the year ($R^2 = 0.74$) (see Figure 5). The gradients of graphs of $k$ in m$^{-1}$ versus suspended solids in mg l$^{-1}$ were 0.066 and 0.056 respectively. This is low in comparison with values for algal cultures and probably reflects the presence of non-algal SS. The relationship between absorbance and $k$ in the period for which both parameters were measured was weaker ($R^2 = 0.53$ and 0.65 for

![Figure 5 SS and $k$ values for SP2](https://iwaponline.com/wst/article-pdf/51/12/143/477021/143.pdf)
SP1 and SP2 respectively), while chlorophyll and $k$ were effectively unrelated ($R^2 < 0.05$ for both ponds).

The absolute value of $k$ on any particular day is of uncertain reliability, due to the method of measurement and in particular to variations in surface irradiance. On average surface irradiance will be less than the clear-sky maximum, although as noted above $k$ values with low correlation or low irradiance were discarded. The results, however, provide an interesting view of the range of $k$ values likely to be encountered for a corresponding range of SS and chlorophyll concentrations.

In addition to the calculation of $k$ values, the relationship between irradiance at a given depth and a number of other parameters was investigated by means of regression equations. Results for SP2 are summarised in Table 1. As might be expected, surface irradiance is the most influential single factor. Suspended solids appear to be a better predictor of irradiance at 0.33 m than 0.15 m, once again confirming the influence of other factors and the problems of measurement in the upper layers. Surface irradiance and SS taken together are the strongest predictors, accounting for over 50% of variation in the top two layers of SP2. Chlorophyll by itself was a poor indicator of irradiance at depth but improved when considered in conjunction with surface irradiance.

For comparative purposes a similar study was carried out from late March to late May in Almaty, Kazakhstan where seasonal and climatic factors have a strong influence: in winter algal biomass concentrations in the water column fall sharply when the ponds freeze, followed by revival in spring. Values of $k$ based on measurements in ponds A(II)1–3 rose rapidly from around 3–5 m$^{-1}$ immediately after thawing in late March to 13–19 m$^{-1}$ by early May, while suspended solids rose from 3–6 to 60–70 mg l$^{-1}$. Pond A(II)3 showed the strongest correlation between SS and $k$ values for the whole period of observation, with $R^2 = 0.63$ and a gradient of 0.14 m$^{-1}$ mg$^{-1}$, showing good agreement with Bowen (2004) and the above results. During this period the pond was not fed, and the suspended solids were therefore mainly of algal origin, arising from nutrients remaining in the pond over winter or released from the bottom sediments in spring. Ponds A(II)1 and 2 showed a weaker correlation between SS and $k$ values in the same period. During this time these ponds were fed on a synthetic wastewater containing suspended solids. The correlation between SS and $k$ was stronger for Pond A(II)2, which was fed on half-strength wastewater, than for Pond A(II)1 fed on full-strength wastewater containing correspondingly more SS ($R^2 = 0.45$ and 0.29 respectively). After peaking in late April, $k$ values for these ponds fell until late May, although SS concentrations remained steady or rose slightly. The correlation of $k$ with chlorophyll concentration in A(II)1 and 2 appeared promising but data were too few for reliability. In general the results suggested that no single factor determines $k$ under non-steady-state conditions, especially where influent SS may have an effect. The maximum $k$ value measured in Ponds A(II)1–3 during this period was 23 m$^{-1}$.

### Table 1

$R^2$ for influence of parameters on irradiance at different depths in SP2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Depth (m)</th>
<th>0.15</th>
<th>0.30</th>
<th>0.53</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface irradiance (SI)</td>
<td>0.47</td>
<td>0.28</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>SS</td>
<td>0.17</td>
<td>0.38</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Absorbance</td>
<td>0.16</td>
<td>0.31</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>SI and SS</td>
<td>0.57</td>
<td>0.50</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>SI and chlorophyll</td>
<td>0.45</td>
<td>0.29</td>
<td>0.10</td>
<td></td>
</tr>
</tbody>
</table>
No detailed analysis of relationships between $k$ and other parameters was carried out for the Almaty A(I) ponds due to insufficient data on SS and chlorophyll, but results for measurements of $k$ values support those from the A(II) ponds, showing a steady rise from the end of April into May. Subsequent falls appear to have been linked with the appearance of large numbers of grazing organisms. The maximum value of $k$ measured during this period was $25 \text{ m}^{-1}$. Values of $k$ measured by this method in Almaty in this period are likely to be relatively reliable due to the high solar elevation and long periods of cloudless weather. None of the results from the A(I), A(II) and Southampton ponds showed a good fit with empirical equations devised for other locations (eg. Xu et al., 2002), indicating that these depend on other parameters.

Conclusions
The light attenuation coefficient $k$ was found to be significantly affected by depth and SS concentrations in the range of values typically found in WSPs. For practical purposes it may often be sufficient to consider $k$ values as constant, but in certain conditions a more sophisticated approach may be needed taking local variation into account. Examples include modelling of WSP start up, or of the annual spring revival in strongly seasonal climates. Typical values for $k$ in ponds appear to lie in the range $5–25 \text{ m}^{-1}$. The use of photodiodes to measure local irradiance proved highly successful. In-pond measurement presents many practical difficulties, however, and the column apparatus may offer a reliable means of measurement under standard conditions. It is recommended that a standardised approach is adopted to the measurement and reporting of $k$ values.

Acknowledgements
The authors wish to acknowledge the support of INTAS Project KZ 96-1864, EU INCO-Copernicus Project CT98-0144, and of the BG Foundation, which enabled them to carry out this work.

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