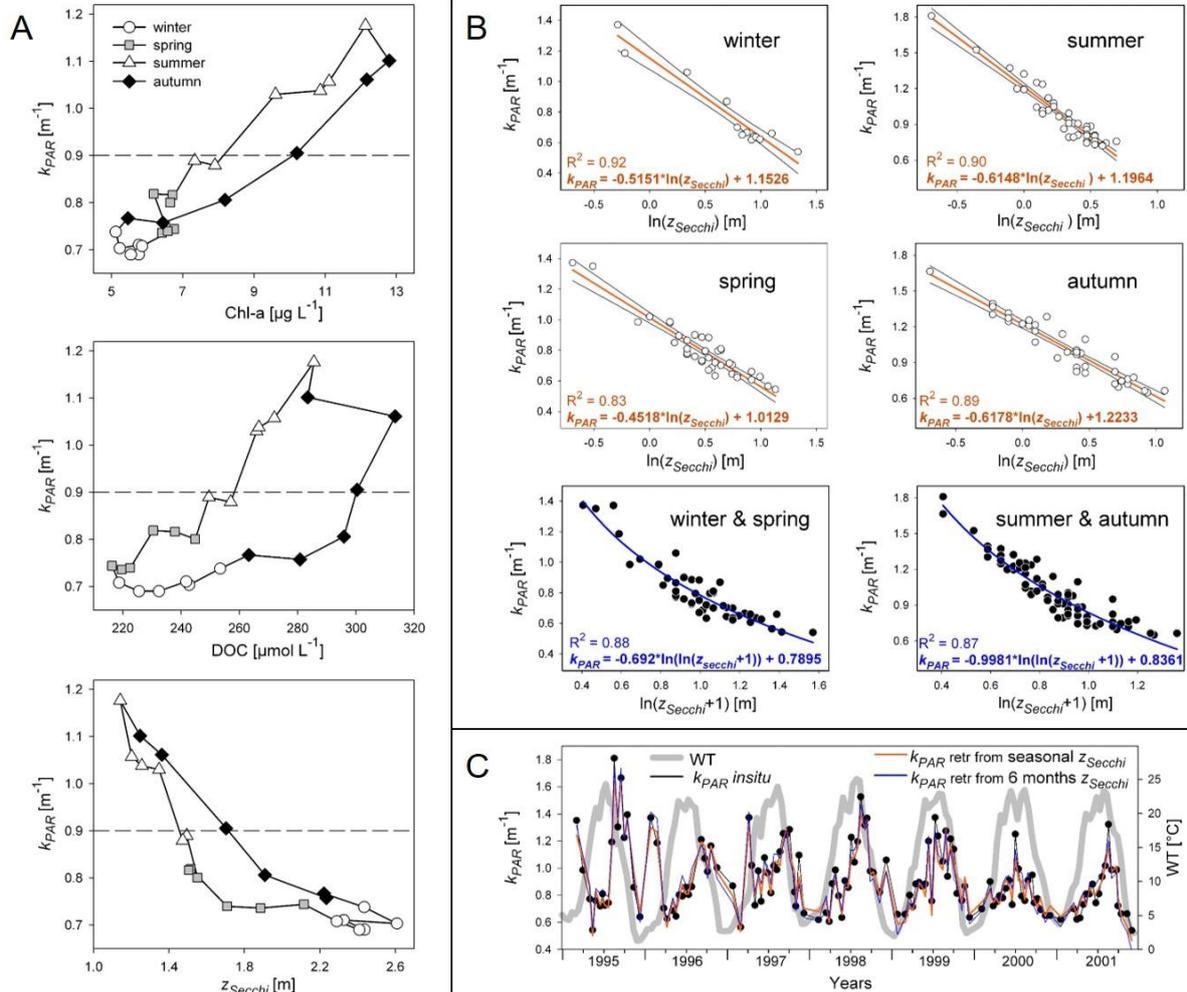


Water transparency expressed by  $z_{Secchi}$ ,  $k_{PAR}$  and  $z_{optimum}$



Supplementary Material\_2, Figure\_S2: Background for retrieving underwater light availability: *in-situ* measurement of water transparency by underwater light attenuation ( $k_{PAR}$ ) and Secchi depth ( $z_{Secchi}$ ) and relations to each other in shallow oxbow lake Alte Donau. A) Annual loop pattern when plotting  $k_{PAR}$  as a function of chlorophyll-a (Chl-a), dissolved organic carbon (DOC), or as  $k_{PAR}$  versus  $z_{Secchi}$ . (symbols represent five-year averages of biweekly data (1997-2001), thus excluding the two specific years of phosphate precipitation in 1995 and 1996, dashed line for  $k_{PAR} = 0.9 m^{-1}$ , see results). B) Functions aimed at retrieving  $k_{PAR}$  from  $\ln(z_{Secchi})$  on the basis of seasons (linear regression model) and of half-year periods winter & spring and summer & autumn (logarithmic regression model) using data of original sampling intervals, 1995 to 2001. C) Time series of *in-situ* measured  $k_{PAR}$  and retrieved  $k_{PAR}$  from seasonal and half-year data from  $z_{Secchi}$  by regression equations displayed in B. Water column temperature (WT) graphically illustrates seasonal progression during the seven-year *in-situ* measurements. See the Methods section of Supplementary Material\_2 for further details.

## METHOD

The method of measuring underwater light availability is presented in greater detail Teubner et al. (2020). As stated there, water transparency was regularly measured with a white Secchi disk ( $z_{Secchi}$ ) at

biweekly (to monthly) intervals from 1993 to 2019 (data for 1987 are integrated from Löffler, 1988). In addition, underwater light attenuation was retrieved from underwater light profile measurements of PAR using a  $4\pi$  quantum sensor (LI-COR) from 1995 to 2001 (sampling site AD2, Fig. 1), primarily used for measures of primary production published, e.g., in Kabas (2004) and Dokulil and Kabas (2018). In the present study, *in-situ* measurements of  $k_{PAR}$  are used to retrieve underwater climate variables from  $z_{Secchi}$  by equations for the reference year 1987 and various restoration periods 1993-2019, which aimed at assessing photic habitat quality for benthic and planktonic assemblages (the photic<sub>>12%</sub> pelagic and photic<sub>>12%</sub> benthic habitat relevant for Figs. 4-7).

Multi-parameter graphs of seasonal loop pattern of optical properties (Fig. S2A) rely on interpolated data over two weeks as regularly applied in this study (see methods “Statistical treatment of time series data”). Original *in-situ* measurements for  $k_{PAR}$  and  $z_{Secchi}$  at weekly (10%) to biweekly (75%) sampling intervals are only presented in S1B and C.

Light attenuation relies on several optical properties, such as light scattering by particles and on light absorption (e.g., Kirk, 1975; Dokulil, 1979; Bricaud and Morel, 1986; Paul, 1989; Gonçalves-Araujo and Markager, 2020). Algae contribute to light attenuation in many ways, i.e., by (1) algal-specific light scattering attributable to planktonic particles of various single-cell architecture and colonial morphotypes, by (2) light utilization of specific wavelengths from the PAR absorption spectrum due to the specific pigment composition assigned to different taxonomic algal groups and by (3) DOC release during their life cycle, mainly dependent on algal physiology as growth and senescence. When comparing the seasonal loop pattern of  $k_{PAR}$  with Chl-a concentrations, or with DOC concentrations or  $z_{Secchi}$ ,  $k_{PAR}$  meets different progressions with the linked parameters over 12 months, illustrating the gradual change of the perspective and of different seasonal drivers of optical properties in the water body. **To reduce the variability of seasonal-driven light attenuation of  $k_{PAR}$  vs  $z_{Secchi}$ ,** we analyzed data of four seasons and the half-year periods winter-spring and summer-autumn. We also considered the latter combination of two seasons in addition to the four seasons because phytoplankton communities are very similar in winter and spring on the one hand and in summer and autumn on the other hand, while winter-spring versus summer-autumn differ significantly as major species change occurs only twice a year, namely from spring to summer and from autumn to winter (Teubner, 2000). It thus it can be expected that major shifts in optical underwater properties occur concurrently.

There is good agreement between *in-situ* measurements of underwater light attenuation and predictions from  $z_{Secchi}$  for both seasonal and half-year periods (Fig. S2\_B). Slightly better fitting results in predicting  $k_{PAR}$  from  $z_{Secchi}$  were, however, obtained from subsets of the individual seasons when compared with the two half-year data sets (regression coefficients see Fig. S2\_B), which is in agreement with Devlin et al. (2008). Thus, linear regression models based on seasonal data from the seven-year data set (Fig. S2\_B), are finally used to predict  $k_{PAR}$  and further parameters for assessing underwater light climate over the whole 28-year study period, relevant for data presentation in Figs. 3B and D, 4, 5, 6. In Figure 5, the horizontal lines display the depth exposed to at least 12% surface ambient light ( $z_{optimum}$ ) for certain trophic classifications. Details about light exposure related to  $z_{optimum}$  see Supplementary Material\_1, Figure\_S1.

## RESULTS

The measurements of ambient light availability by Secchi disk readings ( $z_{Secchi}$ ) and by underwater quantum sensor ( $k_{PAR}$ ) correspond to each other as shown in Fig. S1B. Figure S1A illustrates the seasonal pattern of  $k_{PAR}$  versus Chl-a and DOC, respectively, both of which are known to enhance the

attenuation in the water column as their concentration increases (direct relationship). When plotting the five-year average of light attenuation ( $k_{PAR}$ ) against concentrations of Chl-a and DOC, respectively, low  $k_{PAR}$  are measured during winter and spring associated with a low concentration of Chl-a and DOC, while highest attenuation refers to late summer and early autumn with peak concentrations of Chl-a and DOC. More interesting, however, is the hysteresis loop pattern. For example,  $k_{PAR}$  of  $0.9 \text{ m}^{-1}$  (marked by a line in Fig.S1A) corresponds to relatively low concentrations of Chl-a and DOC, respectively, in early summer as the concentrations of both variables progress towards the annual maximum. However, the same value of attenuation also corresponds to relatively high values of Chl-a and DOC in mid-autumn when the concentrations of both variables are moving towards the annual minimum. While the loop pattern applies to both concentrations here, there are also differences. The five-year average of minimum concentrations of Chl-a is  $5.1 \mu\text{g L}^{-1}$  and increases by a factor of 2.5 to the maximum of  $12.8 \mu\text{g L}^{-1}$ . The concentration of DOC is more evenly distributed with a relatively high minimum concentration of  $216 \mu\text{mol L}^{-1}$  and is increasing by a factor of 1.5 to the maximum of  $313 \mu\text{mol L}^{-1}$ . Moreover, according to the lake phenology during this five-year observation period, the maximum of Chl-a is reached in the second half of August or the first half of September (minimum in late December or early January), while the evolution of DOC is slightly delayed in time and reaches its maximum in the second half of September (minimum in the first half of March, time series graph of phenology is not shown). An annual loop becomes also obvious when plotting  $k_{PAR}$  versus  $z_{Secchi}$  (Fig.S1A), which further demonstrates an inverse relationship for the two parameters (see also correlations in Fig.S1B).

## DISCUSSION

Retrieving ambient light availability for primary producers from  $z_{Secchi}$ , as exemplified in the present study, is complex. Attenuation of incident light in lakes depends in many ways on absorption (e.g., Paul 1989), i.e., by water itself as medium, by DOC (“Gelbstoffe”, coloured dissolved organic matter) and by photosynthetic pigments, and on scattering, i.e., by inorganic and organic particles, as e.g., planktonic algae. These aspects and also sun light quality do not vary stochastically, but change gradually as, e.g., over seasons. To exemplify this for seasonal phytoplankton development, taxa of different pigment spectra (Greisberger and Teubner, 2007) vary in their abundance among seasons with main shifts over half-year periods (Teubner, 2000). Small cell-sized planktonic species such as diatoms, chlorophytes, cryptophytes frequently build up a spring peak while colony forming cyanobacterial blooms accompanied by large-cells of dinoflagellates are peaking in summer (Teubner, 1996; Padisák et al., 2009). Allochthonous (Reitsema et al., 2018; Doyle et al., 2019) and autochthonous sources shape the seasonal pattern of DOC in a lake. In the latter case, DOC exudated by phytoplankton (Larsson and Hagström, 1979; Bjørrisen, 1988) and macrophytes (Ali et al., 2019; Reitsema et al., 2018; Wolters et al., 2019; Reitsema et al., 2021; Somogyi et al., 2022) differs in quality and quantity during vernal growing, peak summer development and autumnal senescent stages and thus gradually within a year. Further relevant here is, that DOC and phytoplankton (expressed as Chl-a concentration) often differ in amount, magnitude and amplitude across seasons (DOC in Figure 1C in Reitner et al., 1999; Chl-a, e.g., in Figure 2 in Tolotti and Thies, 2002), as it could be also exemplified in the present study. These discussed gradual changes explain the annual loop pattern which becomes obvious when plotting Chl-a, DOC and  $z_{Secchi}$  in relation to  $k_{PAR}$  for oxbow lake Alte Donau.

## REFERENCES

- Ali, F., Jilani, G., Fahim, R., Bai, L., Wang, C., Tian, L., and Jiang, H. (2019). Functional and structural roles of wiry and sturdy rooted emerged macrophytes root functional traits in the abatement of nutrients and metals. *Journal of environmental management*, 249, 109330. doi: 10.1016/j.jenvman.2019.109330
- Paul, L. (1989) Interrelationships between optical parameters. *Acta hydrophysica*, Berlin 33 (1), 41-63

- Bjørnsen, P. K. (1988). Phytoplankton exudation of organic matter: Why do healthy cells do it? 1. *Limnology and oceanography*, 33(1), 151-154. doi: 10.4319/lo.1988.33.1.0151
- Bricaud, A., and Morel, A. (1986). Light attenuation and scattering by phytoplanktonic cells: a theoretical modeling. *Appl. Opt.* 25, 571–580. doi: 10.1364/ao.25.000571
- Bricaud, A., and Morel, A. (1986). Light attenuation and scattering by phytoplanktonic cells: a theoretical modeling. *Appl. Opt.* 25, 571–580. doi: 10.1364/ao.25.000571
- Devlin, M. J., Barry, J., Mills, D. K., Gowen, R. J., Foden, J., Sivyer, D., and Tett, P. (2008). Relationships between suspended particulate material, light attenuation and Secchi depth in UK marine waters. *Estuarine, Coastal and Shelf Science*, 79(3), 429-439. doi: 10.1016/j.ecss.2008.04.024
- Dokulil, M. (1979). "Optical properties, colour and turbidity," in *Neusiedlersee: The Limnology of a Shallow Lake in Central Europe*, ed. H. Löffler (Dordrecht: Springer), 151–167. doi: 10.1007/978-94-009-9168-2\_15
- Dokulil, M. T. and Kabas, W. (2018). "Phytoplankton Photosynthesis and Production," in *The Alte Donau: Successful Restoration and Sustainable Management - An Ecosystem Case Study of a Shallow Urban Lake (Aquatic Ecology Series 10)*, eds M. T. Dokulil, K. Donabaum, and K. Teubner (Cham: Springer), 149–163. doi: 10.1007/978-3-319-93270-5\_10
- Doyle, B. C., de Eyto, E., Dillane, M., Poole, R., McCarthy, V., Ryder, E., and E. Jennings (2019). Synchrony in catchment stream colour levels is driven by both local and regional climate. *Biogeosciences*, 16(5), 1053-1071. doi: 10.5194/bg-16-1053-2019
- Gonçalves-Araujo, R., and Markager, S. (2020). Light in the Dark: Retrieving Underwater Irradiance in Shallow Eutrophic Waters From AC-S Measurements. *Front. Mar. Sci.* 7:343. doi: 10.3389/fmars.2020.00343
- Greisberger, S., and Teubner, K. (2007). Does pigment composition reflect phytoplankton community structure in differing temperature and light conditions in a deep alpine lake? An approach using HPLC and delayed fluorescence techniques 1. *J. Phycol.* 43, 1108–1119. doi: 10.1111/j.1529-8817.2007.00404.x
- Kabas, W. (2004). *Die Veränderungen der Primärproduktion in der Alten Donau in den Jahren 1995–2002. Mit einem Methodenvergleich.* Ph.D. thesis, University of Vienna, Wien.
- Kirk, J. T. O. (1975). A theoretical analysis of the contribution of algal cells to the attenuation of light within natural waters I. General treatment of suspensions of pigmented cells. *New Phytol.* 75, 11–20. doi: 10.1111/j.1469- 8137.1975.tb01366.x
- Larsson, U., and Hagström, A. (1979). Phytoplankton exudate release as an energy source for the growth of pelagic bacteria. *Marine biology*, 52(3), 199-206. doi: 10.1007/BF00398133
- Padisák, J., Crossetti, L. O., and Naselli-Flores, L. (2009). Use and misuse in the application of the phytoplankton functional classification: a critical review with updates. *Hydrobiologia*, 621(1), 1-19. doi: 10.1007/s10750-008-9645-0
- Paul, L. (1989) Interrelationships between optical parameters. *Acta hydrophysica*, Berlin 33 (1), 41-63
- Reitner, B., Herzig, A., and Herndl, G. J. (1999). Dynamics in bacterioplankton production in a shallow, temperate lake (Lake Neusiedl, Austria): evidence for dependence on macrophyte production rather than on phytoplankton. *Aquatic Microbial Ecology*, 19(3), 245-254. doi:10.3354/ame019245
- Reitsema, R. E., Meire, P., and Schoelynck, J. (2018). The future of freshwater macrophytes in a changing world: dissolved organic carbon quantity and quality and its interactions with macrophytes. *Frontiers in plant science*, 9, 629. doi: 10.3389/fpls.2018.00629
- Reitsema, R. E., Preiner, S., Meire, P., Hein, T., Dai, Y., and Schoelynck, J. (2021). Environmental control of macrophyte traits and interactions with metabolism and hydromorphology in a groundwater-fed river. *River Research and Applications*, 37(2), 294-306. doi: 10.1002/rra.3708
- Somogyi, B., Boros, E., Szabó-Tugyi, N., Kovács, A. W., and Vörös, L. (2022). Dense macrophyte cover has significant structural and functional influence on planktonic microbial communities leading to bacterial success. *Science of The Total Environment*, 154576. doi: 10.1016/j.scitotenv.2022.154576
- Teubner K., Teubner I., Pall K., Kabas W., Tolotti M., Ofenböck T. and Dokulil M.T. (2020). New Emphasis on Water Transparency as Socio-Ecological Indicator for Urban Water: Bridging Ecosystem Service Supply and Sustainable Ecosystem Health. *Front. Environ. Sci.* 8:573724. doi: 10.3389/fenvs.2020.573724
- Teubner, K. (1996) *Struktur und Dynamik des Phytoplanktons in Beziehung zur Hydrochemie und Hydrophysik der Gewässer: Eine multivariate statistische Analyse an ausgewählten Gewässern der Region Berlin-Brandenburg.* Ph.D thesis, Dept. Ecophysiology, Humboldt University Berlin: 232pp
- Teubner, K. (2000) Synchronised changes of planktonic cyanobacterial and diatom assemblages in North German waters reduce seasonality to two principal periods. *Arch Hydrobiol, Spec Iss Adv Limnol* 55, 564–580
- Tolotti, M., and Thies, H. (2002). Phytoplankton community and limnochemistry of Piburger See (Tyrol, Austria) 28 years after lake restoration. *Journal of Limnology*, 61(1), 77-88.
- Wolters, J. W., Reitsema, R. E., Verdonschot, R. C., Schoelynck, J., Verdonschot, P. F., and Meire, P. (2019). Macrophyte-specific effects on epiphyton quality and quantity and resulting effects on grazing macroinvertebrates. *Freshwater Biology*, 64(6), 1131-1142. doi: 10.1111/fwb.13290