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Jessica S. Turner
*Virginia Institute of Marine Science*

Kelsey A. Fall

Carl T. Friedrichs
*Virginia Institute of Marine Science*



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ESSAY

# Clarifying water clarity: A call to use metrics best suited to corresponding research and management goals in aquatic ecosystems

*Jessica S. Turner*[1a]*, *Kelsey A. Fall*[2], *Carl T. Friedrichs*[1]
[1]Virginia Institute of Marine Science, William & Mary, Gloucester Point, Virginia; [2]U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi

### *Scientific Significance Statement*

Water clarity is a subjective term and can be measured multiple ways. Different metrics such as light attenuation and Secchi depth vary in effectiveness depending on the research or management application. In this essay, we argue that different questions merit different water clarity metrics. In coastal and inland waters, empirical relationships to estimate light attenuation can yield clarity estimates that either under- or overestimate the underwater light climate for restoration goals, such as potential habitat available for submerged aquatic vegetation. Best practices in reporting water clarity measurements include regionally specific, temporally representative calibrations and communicating the metric that was actually measured. An intentional choice of the water clarity metric best suited to the research or management question yields the most useful results.

The term "water clarity" is inherently ambiguous. Water clarity generally refers to the distance that light penetrates through water, as well as the visibility of objects through water. In lakes, rivers, estuaries, coastal zones, and the open ocean, water clarity is an essential measurement for monitoring programs and a wide variety of research applications. For example, water clarity is used to assess habitat quality for submerged aquatic vegetation (SAV), to study visual predation, and to model primary production. Water clarity is measured using multiple methods, some focused on the depth of light penetration, some based on the depth of object visibility, and others based on the amounts of components present (Fig. 1).

General metrics presented here include: Secchi disk depth ($Z_{SD}$) (Secchi and Cialdi 1866; Tyler 1968; Preisendorfer 1986), the downwelling and scalar light attenuation coefficients of photosynthetically active radiation ($K_d$(PAR) and $K_o$(PAR)) (Kirk 1994), turbidity (Zaneveld et al. 1980; Davies-Colley and Smith 2001; Sampedro and Salgueiro 2015; Eidam et al. 2022), and beam attenuation (Bishop 1999). In this paper, the terms $K_d$ and $K_o$ will refer to $K_d$(PAR) and $K_o$(PAR). $Z_{SD}$, $K_o$, and $K_d$ are apparent optical properties, descriptors of water bodies that depend on both the substances present and the light field (Mobley 2022). Component-based metrics include colored dissolved organic matter (CDOM) commonly measured by its light absorption (aCDOM; $m^{-1}$) (Green and Blough 1994) or

*Correspondence: jturner@uconn.edu

[a]Present address: Department of Marine Sciences, University of Connecticut, Groton, Connecticut, USA

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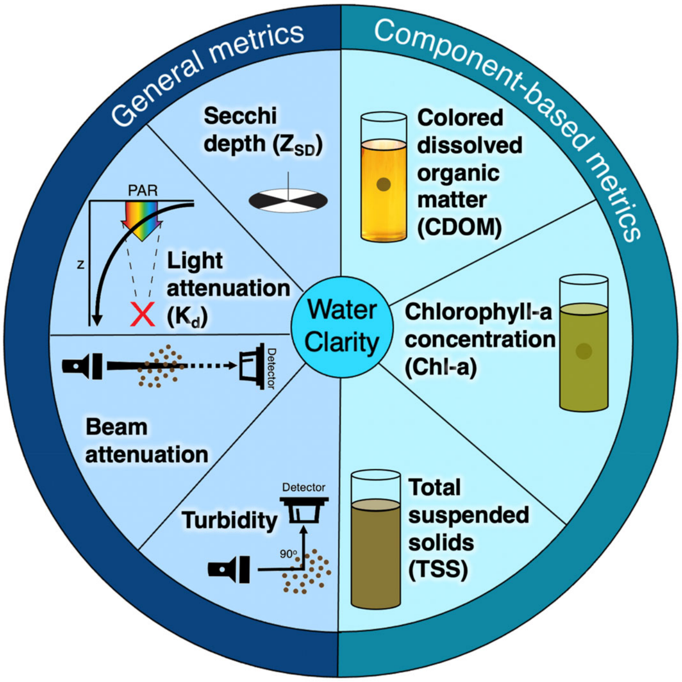


**Fig. 1.** Common metrics used to monitor water clarity. General metrics presented here include Secchi depth ($Z_{SD}$), light attenuation of photosynthetically active radiation ($K_d$(PAR); referred to in this paper as $K_d$), turbidity, and beam attenuation. Metrics identified with specific components of the water column include colored dissolved organic matter (CDOM), total suspended solids concentration (TSS) (also known as suspended particulate matter, or SPM), and chlorophyll *a* concentration (Chl *a*). Some symbols are adapted from IAN UMCES media library.

its fluorescence (Stedmon et al. 2003), chlorophyll *a* pigment concentration (Chl *a*; mg m$^{-3}$) commonly measured by its fluorescence (Holm-Hansen et al. 1965; Welschmeyer 1994), and total suspended solids concentration (TSS; mg L$^{-1}$) also known as suspended particulate matter, total suspended matter, or suspended sediment concentration (Ball 1964). For CDOM and Chl *a*, conversions from fluorescence to aCDOM and Chl *a* pigment concentration may need to account for confounding factors, such as non-fluorescing components, Chl *a* daytime nonphotochemical quenching, and high-scattering environments that can affect the strength of the signal (Oestreich et al. 2016; Cremella et al. 2018; Carberry et al. 2019).

In this essay, we share a case study from the York River estuary (henceforth referred to as the York), a subestuary of the Chesapeake Bay. This location illustrates a clarity measurement puzzle, the likes of which occurs in many other water bodies globally. The dataset includes coincident measurements of Chl *a*, turbidity, $K_o$, and $Z_{SD}$ from Fall (2020); coincident measurements of Chl *a*, turbidity, and $K_d$ from the Chesapeake Bay National Estuarine Research Reserve in Virginia (CBNERR-VA); and coincident measurements of $K_d$ and $Z_{SD}$ from the Chesapeake Bay Program (CBP) Water Quality monitoring program, all from 2014 to 2016 (Turner et al. 2022). Fall (2020) data were collected irregularly in time at eight stations within the York (Fig. 2A). CBNERR-VA and CBP data were collected once or twice per month at the Goodwin Islands and WE4.2 long-term monitoring sites, respectively (Fig. 2A).

## *Light attenuation is often estimated from other water clarity metrics*

### Estimating light attenuation from Secchi depth is problematic

The simple hyperbolic relationship between $K_d$ and $Z_{SD}$ is widely represented as $K_d = \alpha / Z_{SD}$ such that the product of $K_d \times Z_{SD} = \alpha$ (Holmes 1970). However, often $K_d$ and $Z_{SD}$ do not adhere to a consistent relationship described by a constant $\alpha$. The value of $\alpha$ has been found to vary widely in estuaries, lakes, and other aquatic environments across many latitudes, hydrologies, and climatic conditions (Lee et al. 2018; Bowers et al. 2020). Consequently, in turbid environments it is often disadvantageous to calibrate $\alpha$ (Preisendorfer 1986). In the present study, the York serves as an extreme example of this variability (Fig. 2B).

Instead, what information can be gained from the decoupling of $K_d$ and $Z_{SD}$? First, if the goal is to understand light penetration, measuring $K_d$ directly will be most useful (Table 1). Second, if the goal is instead to understand transparency or visibility, measuring $Z_{SD}$ alone may suffice. Finally, simultaneous measurement of $K_d$ and $Z_{SD}$ can be used to gain insight into how dissolved and particulate constituents interact with light, since the mismatch between $K_d$ and $Z_{SD}$ yields more information about light-blocking substances in the water.

This mismatch between $K_d$ and $Z_{SD}$ provides useful information about the constituents that limit light penetration. In moderately turbid waters, $K_d$ often has a smaller value (i.e., indicates clearer water) than that predicted based on a simple relationship with $Z_{SD}$ ($\alpha < 1.45$). Smaller $K_d$ values than expected based on $Z_{SD}$ are often attributed to the properties of the suspended particles (Hou et al. 2007), such as reduced visibility of the disk due to increased forward scattering by small organic particles (Hernández and Gocke 1988; Armengol et al. 2003; Effler and Peng 2012). For example, changes in particle scattering may contribute to the long-term shallowing of $Z_{SD}$ in the Chesapeake Bay while $K_d$ indicates minimal change or even an improvement in clarity (Gallegos et al. 2011; Harding et al. 2016; Testa et al. 2019; Turner et al. 2021). In the other direction, high quantities of CDOM can cause deeper $Z_{SD}$ compared to what $K_d$ would predict, due to high visibility yet rapid light absorption ($\alpha > 1.45$) (Pedersen et al. 2014).

Water clarity is critical for SAV, which requires light penetration to depth for photosynthesis. During SAV restoration

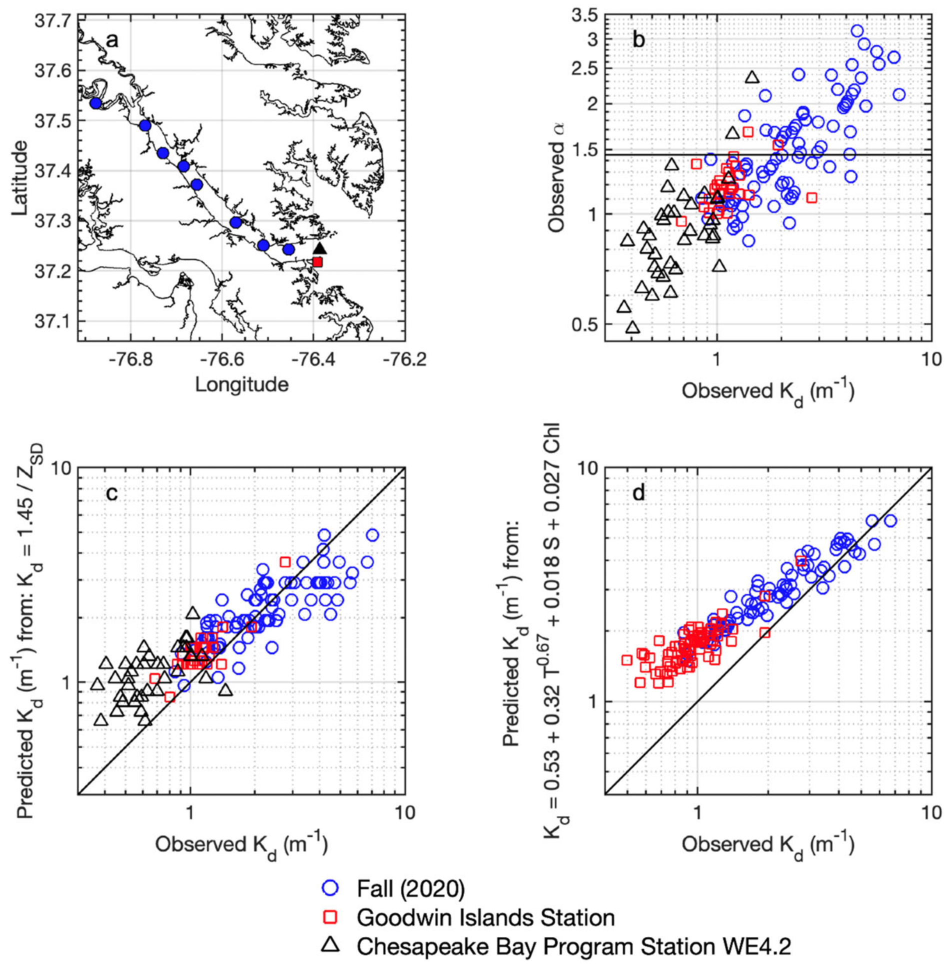


**Fig. 2.** York River estuary case study location and water clarity data. Blue circles indicate cruise measurements from Fall (2020). Red squares indicate Chesapeake Bay National Estuarine Research Reserve in Virginia measurements at the Goodwin Islands station. Black triangles indicate Chesapeake bay Program cruise measurements at station WE4.2. (**A**) Map of data collection locations in southwestern Chesapeake Bay. (**B**) Relationship between directly measured light attenuation coefficient ($K_d$) and observed $\alpha$ (the product $K_d \times$ Secchi depth ($Z_{SD}$)), black line indicates commonly used $\alpha = 1.45$. (**C**) Directly measured $K_d$ vs. predicted $K_d$ estimated from $1.45/Z_{SD}$. (**D**) Directly measured $K_d$ vs. predicted $K_d$ estimated using the York River (Virginia Group 2) attainment criteria in USEPA (2008), where S = salinity, T = turbidity (NTU), and Chl = chlorophyll *a* concentration (mg $m^{-3}$). Black lines in (**C**) and (**D**) indicate a 1 : 1 relationship between observed $K_d$ and predicted $K_d$. In all subplots, Fall (2020) blue circles indicate scalar light attenuation ($K_o$) measurements in place of downwelling light attenuation ($K_d$). Values for $K_d$ and $K_o$ differ minimally in turbid, optically deep waters (Kirk 1994; Tilzer et al. 1995).

work, the use of one water clarity metric to estimate another can over- or under-estimate depth limits of habitats. For example, in a fjord in Denmark, $Z_{SD}$ deepened over time, but $K_d$ remained relatively high due to large CDOM concentrations, causing $Z_{SD}$ to overestimate the potential habitat for SAV (Pedersen et al. 2014). Consequently, $K_d$ should be used rather than $Z_{SD}$ as a proxy for light penetration depths to infer SAV habitat quality, since the plants collect plane irradiance (Zimmerman 2003, 2006).

## Estimating $K_d$ from multiple metrics

Researchers and monitoring programs frequently estimate $K_d$ from a subset of other metrics. In oligotrophic waters, these relationships are based on the contributions to $K_d$ mainly from phytoplankton; thus, $K_d$ is most commonly derived from Chl *a* (Smith and Baker 1978; Baker and Smith 1982; Kim et al. 2015). In coastal waters, estuaries, and many lakes and rivers, $K_d$ is estimated from not only Chl *a*, but also CDOM (or salinity) and TSS (Woodruff 1996; Gallegos 2001; Fear et al. 2004; Xu et al. 2005; USEPA 2008; Feng et al. 2015; Cerco and Noel 2017; Turner et al. 2021). Other estimations of $K_d$ from multiple metrics employ semi-analytical relationships (e.g., Gallegos 2001; Lee et al. 2005, 2007; Zimmerman et al. 2015), enabling the use of satellite remote sensing to estimate water clarity at high spatial resolutions relevant to lakes and estuaries (Lee et al. 2015, 2016).

**Table 1.** Usefulness of common water clarity metrics for different applications.

| Variable | Other names or related metrics | Units | Recommended applications |
|---|---|---|---|
| $K_d$ | $K_o$, $K_d^{-1}$, PLW, light extinction coefficient | $m^{-1}$ | • Submerged aquatic vegetation<br>• Benthic micro-algae<br>• Coral reefs<br>• Photosynthesis<br>• Phytoplankton dynamics<br>• Heat transfer |
| $Z_{SD}$ | Transparency, visibility | m | • Visibility and transparency<br>• Property values and recreation<br>• Fish predation on mesopredators and related behaviors<br>• Citizen science and community engagement<br>• Comparison to long-term historical data sets |
| Turbidity | OBS, side-scattering | FNU, FTU, NTU | • Total light scattering by particles<br>• Long-term measurements with simple but resilient sensors |
| Beam attenuation | Light transmission, transmissometry | $m^{-1}$ | • Proxy for particulate organic carbon in oligotrophic waters<br>• Long-term measurements with simple but resilient sensors |
| aCDOM | CDOM, gelbstoff, gilvin | $m^{-1}$ | • Dissolved substances from rivers and wetlands<br>• Dissolved substances produced by marine plankton<br>• Contribution of dissolved substances to spectral $K_d$ |
| Chl *a* | Chl *a* fluorescence | mg $m^{-3}$ | • Primary production<br>• Contribution of algae to $K_d$<br>• Phytoplankton dynamics<br>• Harmful algal blooms<br>• Long-term measurements with simple but resilient sensors |
| TSS | TSM, SPM, SSC | mg $L^{-1}$ | • Marsh accretion<br>• Contribution of particles to $K_d$<br>• Sediment seabed modeling<br>• Mass transport of sediments<br>• Health of oyster reefs |

In the Chesapeake Bay and its tributaries, monitoring programs map $K_d$ spatially in shallow waters to assess habitat potential for SAV, making use of an empirical equation with turbidity, salinity (as a proxy for CDOM), and Chl *a*. These latter three metrics are collected with a flow-through method, increasing the temporal and spatial coverage. $K_d$ is measured directly at a few validation stations, but it is also often calculated from regionally determined empirical relationships with turbidity, salinity, and Chl *a*. This approach groups multiple subregions and time periods together to generate a relationship that describes a wider distribution of conditions (Dennison et al. 1993; USEPA 2003, 2007, 2008; Moore et al. 2009; Reay 2009; Tango and Batiuk 2013).

## Best practices for estimating water clarity using available resources

### Report the metric that was measured

Perhaps the most important practice in measuring water clarity is to report the actual metric used. Some studies use one term when the metric analyzed does not represent what the term implies. For example, Wang et al. (2013) describe patterns in $K_d$ when the metric measured was actually $Z_{SD}$, from which $K_d$ was derived using the conventional $K_d = 1.45/Z_{SD}$ relationship that is inherently less useful in turbid waters (Fig. 2B,C). However, if an empirical equation between metrics is required due to cost, sampling resolution needs, or other factors, then the method should be clearly communicated (e.g., CDOM estimated from salinity), and the cross-calibration data used should be made available. In the case of light attenuation, the use of a scalar ($K_o$) or downwelling ($K_d$) coefficient should be reported explicitly.

### Measure $K_d$ with deep light profiles

In some cases, $K_d$ may be over- or under-estimated due to measurement error when light profiles do not extend deep enough into the water column. Collecting downwelling or scalar irradiance depth profiles over varying depth ranges can result in inconsistent estimates of the best-fit $K_d$ most relevant to the full photic zone, particularly when irradiance is not measured to a deep enough light penetration depth (Lee et al. 2018). Whenever possible, light profiles should be measured to the depth of 1% illumination to avoid measurement error.

### Locally calibrated

Empirical models for $K_d$ need to be locally calibrated because the characteristics of the water's dissolved and particulate matter vary greatly, sometimes at a fine spatial scale. In the Chesapeake Bay, a single $K_d$ relationship applies only to some subregions, but not all. In smaller tributary rivers such as the York and Elizabeth Rivers, there is relatively more CDOM, while in larger tributary rivers such as the Potomac and Susquehanna Rivers, there is relatively less CDOM than salinity would predict (Cerco and Noel 2017). The diversity in contributions to $K_d$ likely results from the variety of river inputs; while the largest rivers have mountainous uplands and deliver relatively more sediment, the smaller rivers drain coastal plains and wetlands and deliver relatively more CDOM (Najjar et al. 2020; Henderson and Bukaveckas 2022). In addition, the response of $K_d$ to TSS may vary strongly with distance along a given estuary due to systematic variations in suspended sediment floc size, density, and organic content (Yard 2003; Fall et al. 2020).

### Temporally representative

Ideally, a relationship used to estimate $K_d$ should incorporate measurements representative of different times and conditions, so that the variability over the targeted dataset is captured. A calibration performed during one season or tidal stage will likely not apply to the entire dataset of interest. In the York, an empirical relationship developed during a certain set of years (pre-2008) underestimates clarity compared to observations collected years later (Fig. 2D). The disagreement may be in part because 2014–2016 were hydrologically dry years in the Chesapeake Bay with lower nutrient and TSS concentrations, and generally clearer water than the early 2000s. These types of discrepancies have implications for management and restoration of important habitats. In the York example (Fig. 2D), directly measured $K_d$ would predict a greater spatial area suitable for SAV, while the empirical relationship from USEPA (2008) underestimates light availability. It could be argued that this somewhat conservative underestimation of habitat is a minor problem. However, overestimating light availability would result in negative ecological implications such as overpredicting the amount of suitable habitat for SAV (e.g., Pedersen et al. 2014).

## *Choose wisely: Select a water clarity metric targeting the research or management goal*

When planning water clarity measurements, it is recommended to select the most useful metric or metrics according to the specific application (Table 1). For example, if $K_d$ can be measured directly, it should be measured using a light sensor rather than estimated from other metrics. If an empirical relationship or a simple sensor is needed due to cost or other factors, use of best practices is recommended. When relevant to the goal, even the simplest water clarity measurements are valuable for environmental monitoring and restoration, whether by citizen scientists, non-profit organizations, or local sampling programs.

$K_d$ is the most relevant measure of water clarity for most research in aquatic ecosystems. $K_d$ is well-suited to research involving benthic autotrophs such as SAV in estuaries (Zimmerman 2003; Moore 2004) and lakes (Schwarz et al. 1996; Borowiak et al. 2017), benthic microalgae (Newell et al. 2002), kelp forests (Graham et al. 2007; Tait et al. 2021), and coral reef habitats (Baird et al. 2016; Jones et al. 2016). Scalar or downwelling light attenuation ($K_o$ or $K_d$) may be more appropriate for different applications. For phytoplankton photosynthesis, $K_o$ better represents the amount of total light energy available to cells from all directions. For benthic macrophytes, $K_d$ is more suitable because plants' flat leaves collect downwelling light (Zimmerman 2003, 2006). For citizen scientists or non-profit organizations wishing to measure $K_d$ directly, low cost light intensity loggers are available as an alternative to expensive traditional sensors (Long et al. 2012).

$Z_{SD}$ is a representative measurement of visibility. $Z_{SD}$ applies to human perception of water clarity (Keeler et al. 2015; West et al. 2016) and water clarity's effect on property values (Klemick et al. 2018). $Z_{SD}$ is also relevant for sighted animals and their trophic interactions, such as visual foraging efficiency of zooplankton and fish (Aksnes 2007; Aksnes et al. 2004; Goździejewska and Kruk 2022) and interactions between predators and mesopredators (Benfield and Minello 1996; Baptist and Leopold 2010; Lunt and Smee 2014; Reustle and Smee 2020). $Z_{SD}$ also serves an important role in citizen science and community engagement (Crooke et al. 2017; Pitarch 2020) and in maintaining especially long time-series (Jassby et al. 2003; Opdal et al. 2019).

TSS is a representative measurement of particles that block light, directly affecting water clarity. However, TSS is truly a measurement of the mass of suspended particles rather than light penetration. Therefore, TSS may be most useful for research applications that benefit from quantifying the mass of sediments present in the water column, such as questions involving sediment resuspension, shoreline erosion, or river inputs (Fall et al. 2014; Palinkas et al. 2019; Tarpley et al. 2019; Moriarty et al. 2020). TSS can be a useful metric for shellfish research, since high concentrations of sediments can clog oyster gills and can blanket oyster reefs via deposition (Luckenbach et al. 1999; Beck et al. 2011; Gernez et al. 2014).

Chl *a*, turbidity, and beam attenuation are useful in that recent technologies allow sensors to be deployed at relatively low cost for long periods of time. Platforms like buoys, moorings, and floats are well suited for optical in situ sensors, thus many programs use these sensors for continuous long-term monitoring (Boss et al. 2018). Chl *a* and turbidity are often used in the field as stand-alone metrics. Chl *a* provides more information about the effects of phytoplankton on the underwater light climate, while turbidity provides more information about light scattering by suspended particles (Boss et al. 2009).

Looking to the future, the ability to collect data at high spatial and temporal resolution by a wider diversity of researchers is critical. While these measurements may be less directly representative of $K_d$ in dynamic systems, their importance should not be diminished. Provided that calibrations are well-performed, these simple longer-term measurements represent a fruitful way forward in water clarity research and monitoring. When factors contributing to light attenuation are not well understood, multiple measurements are needed to evaluate the relative magnitude and importance of the factors affecting light reduction. Use of multiple metrics is especially important in management of the causes of changes in water clarity.

## References

Aksnes, D. L. 2007. Evidence for visual constraints in large marine fish stocks. Limnol. Oceanogr. **52**: 198–203. doi:10.4319/lo.2007.52.1.0198

Aksnes, D. L., J. Nejstgaard, E. Sædberg, and T. Sørnes. 2004. Optical control of fish and zooplankton populations. Limnol. Oceanogr. **49**: 233–238. doi:10.4319/lo.2004.49.1.0233

Armengol, J., L. Caputo, M. Comerma, C. Feijoó, J. C. García, R. Marcé, E. Navarro, and J. Ordoñez. 2003. Sau reservoir's light climate: Relationships between Secchi depth and light extinction coefficient. Limnetica **22**: 195–210. doi:10.23818/limn.22.13

Baird, M. E., and others. 2016. Remote-sensing reflectance and true colour produced by a coupled hydrodynamic, optical, sediment, biogeochemical model of the Great Barrier Reef, Australia: Comparison with satellite data. Environ. Model. Softw. **78**: 79–96. doi:10.1016/j.envsoft.2015.11.025

Baker, K. S., and R. C. Smith. 1982. Bio-optical classification and model of natural waters. Limnol. Oceanogr. **27**: 500–509. doi:10.4319/lo.1982.27.3.0500

Ball, D. F. 1964. Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. J. Soil Sci. **15**: 84–92. doi:10.1111/j.1365-2389.1964.tb00247.x

Baptist, M. J., and M. F. Leopold. 2010. Prey capture success of sandwich terns sterna sandvicensis varies non-linearly with water transparency. Ibis **152**: 815–825. doi:10.1111/j.1474-919X.2010.01054.x

Beck, M. W., and others. 2011. Oyster reefs at risk and recommendations for conservation, restoration, and management. BioScience **61**: 107–116. doi:10.1525/bio.2011.61.2.5

Benfield, M. C., and T. J. Minello. 1996. Relative effects of turbidity and light intensity on reactive distance and feeding of an estuarine fish. Environ. Biol. Fishes **46**: 211–216. doi:10.1007/BF00005223

Bishop, J. K. B. 1999. Transmissometer measurement of POC. Deep-Sea Res. I Oceanogr. Res. Pap. **46**: 353–369. doi:10.1016/S0967-0637(98)00069-7

Borowiak, D., K. Bociąg, K. Nowiński, and M. Borowiak. 2017. Light requirements of water lobelia (*Lobelia dortmanna* L.). Limnol. Rev. **17**: 171–182. doi:10.1515/limre-2017-0016

Boss, E., and others. 2009. Comparison of inherent optical properties as a surrogate for particulate matter concentration in coastal waters. Limnol. Oceanogr.: Methods **7**: 803–810. doi:10.4319/lom.2009.7.803

Boss, E., C. R. Sherwood, P. Hill, and T. Milligan. 2018. Advantages and limitations to the use of optical measurements to study sediment properties. Appl. Sci. **8**: 2692. doi:10.3390/app8122692

Bowers, D. G., E. M. Roberts, A. M. Hoguane, K. A. Fall, G. M. Massey, and C. T. Friedrichs. 2020. Secchi disk measurements in turbid water. J. Geophys. Res.: Oceans **125**: e2020JC016172. doi:10.1029/2020jc016172

Carberry, L., C. Roesler, and S. Drapeau. 2019. Correcting in situ chlorophyll fluorescence time-series observations for nonphotochemical quenching and tidal variability reveals nonconservative phytoplankton variability in coastal waters. Limnol. Oceanogr.: Methods **17**: 462–473. doi:10.1002/lom3.10325

Cerco, C. F., and M. R. Noel. 2017, *The 2017 Chesapeake Bay water quality and sediment transport model*. US Environmental Protection Agency Chesapeake Bay Program. http://www.chesapeake.org/stac/presentations/277_20170501_Cerco%20and%20Noel%202017_WQSTM%20Draft%20Report.pdf

Cremella, B., Y. Huot, and S. Bonilla. 2018. Interpretation of total phytoplankton and cyanobacteria fluorescence from cross-calibrated fluorometers, including sensitivity to turbidity and colored dissolved organic matter. Limnol. Oceanogr.: Methods **16**: 881–894. doi:10.1002/lom3.10290

Crooke, B. C., L. McKinna, and I. Cetinić. 2017. From toes to top-of-atmosphere: Fowler's sneaker depth index of water clarity for the Chesapeake Bay. Opt. Express **25**: A361–A374. doi:10.1364/OE.25.00A361

Davies-Colley, R. J., and D. G. Smith. 2001. Turbidity, suspended sediment, and water clarity: A review. J. Am. Water Resour. Assoc. **37**: 1085–1101. doi:10.1111/j.1752-1688.2001.tb03624.x

Dennison, W. C., R. J. Orth, K. A. Moore, J. C. Stevenson, V. Carter, S. Kollar, P. W. Bergstrom, and R. A. Batiuk. 1993. Assessing water quality with submersed aquatic vegetation. Bioscience **43**: 86–94.

Effler, S. W., and F. Peng. 2012. Light-scattering components and Secchi depth implications in Onondaga Lake, New York, USA. Fundam. Appl. Limnol. **179**: 251–265. doi:10.1127/1863-9135/2012/0177

Eidam, E. F., T. Langhorst, E. B. Goldstein, and M. McLean. 2022. OpenOBS: Open-source, low-cost optical backscatter sensors for water quality and sediment-transport research. Limnol. Oceanogr.: Methods **20**: 46–59. doi:10.1002/lom3.10469

Fall, K. A. 2020, *Influence of suspended particle size and composition on particle image processing, estuarine floc fractal properties, and resulting estuarine light attenuation*. Virginia Insitute of Marine Science, William & Mary.

Fall, K., C. Harris, C. Friedrichs, J. Rinehimer, and C. Sherwood. 2014. Model behavior and sensitivity in an application of the cohesive bed component of the community sediment transport modeling system for the York River estuary, VA, USA. J. Mar. Sci. Eng. **2**: 413–436. doi:10.3390/jmse2020413

Fall, K. A., C. T. Friedrichs, G. M. Massey, D. G. Bowers, and S. J. Smith. 2020. The importance of organic content to fractal floc properties in estuarine surface waters: Insights from video, LISST, and pump sampling. J. Geophys. Res.: Oceans **126**: e2020JC016787. doi:10.1029/2020jc016787

Fear, J., T. Gallo, N. Hall, J. Loftin, and H. Paerl. 2004. Predicting benthic microalgal oxygen and nutrient flux responses to a nutrient reduction management strategy for the eutrophic Neuse River estuary, North Carolina, USA. Estuar. Coast. Shelf Sci. **61**: 491–506. doi:10.1016/j.ecss.2004.06.013

Feng, Y., M. A. M. Friedrichs, J. Wilkin, H. Tian, Q. Yang, E. E. Hofmann, J. D. Wiggert, and R. R. Hood. 2015. Chesapeake Bay nitrogen fluxes derived from a land-estuarine ocean biogeochemical modeling system: Model description, evaluation, and nitrogen budgets. J. Geophys. Res.: Biogeo. **120**: 1666–1695. doi:10.1002/2015JG002931

Gallegos, C. L. 2001. Calculating optical water quality targets to restore and protect submersed aquatic vegetation: Overcoming problems in partitioning the diffuse attenuation coefficient for photosynthetically active radiation. Estuaries **24**: 381–397. doi:10.2307/1353240

Gallegos, C. L., P. J. Werdell, and C. R. McClain. 2011. Long-term changes in light scattering in Chesapeake Bay inferred from Secchi depth, light attenuation, and remote sensing measurements. J. Geophys. Res.: Oceans **116**: C00H08. doi:10.1029/2011JC007160

Gernez, P., L. Barille, A. Lerouxel, C. Mazeran, A. Lucas, and D. Doxoran. 2014. Remote sensing of suspended particulate matter in turbid oyster-farming ecosystems. J. Geophys. Res.: Oceans **119**: 7277–7294. doi:10.1002/2014JC010055

Goździejewska, A. M., and M. Kruk. 2022. Zooplankton network conditioned by turbidity gradient in small anthropogenic reservoirs. Sci. Rep. **12**: 3938. doi:10.1038/s41598-022-08045-y

Graham, M. H., B. P. Kinlan, L. D. Druehl, L. E. Garske, and S. Banks. 2007. Deep-water kelp refugia as potential hotspots of tropical marine diversity and productivity. Proc. Natl. Acad. Sci. USA **104**: 16576–16580. doi:10.1073/pnas.0704778104

Green, S. A., and N. V. Blough. 1994. Optical absorption and fluorescence properties of chromophoric dissolved organic matter in natural waters. Limnol. Oceanogr. **39**: 1903–1916. doi:10.4319/lo.1994.39.8.1903

Harding, L. W., C. L. Gallegos, E. S. Perry, W. D. Miller, J. E. Adolf, M. E. Mallonee, and H. W. Paerl. 2016. Long-term trends of nutrients and phytoplankton in Chesapeake Bay. Estuaries Coasts **39**: 664–681. doi:10.1007/s12237-015-0023-7

Henderson, R., and P. A. Bukaveckas. 2022. Factors governing light attenuation in upper segments of the James and York estuaries and their influence on primary producers. Estuaries Coasts **45**: 470–484. doi:10.1007/s12237-021-00983-6

Hernández, C. A., and K. Gocke. 1988. Productividad primaria en la Cienága Grande de Santa Marta, Colombia. Inst. Invest. Mar. Punta Betin **19**: 101–119.

Holmes, R. W. 1970. The Secchi disk in turbid coastal waters. Limnol. Oceanogr. **15**: 688–694. doi:10.4319/lo.1970.15.5.0688

Holm-Hansen, O., C. J. Lorenzen, R. W. Holmes, and J. D. H. Strickland. 1965. Fluorometric determination of chlorophyll. ICES J. Mar. Sci. **30**: 3–15. doi:10.1093/icesjms/30.1.3

Hou, W., Z. Lee, and A. D. Weidemann. 2007. Why does the Secchi disk disappear? An imaging perspective. Opt. Express **15**: 2791. doi:10.1364/oe.15.002791

Jassby, A. D., J. E. Reuter, and C. R. Goldman. 2003. Determining long-term water quality change in the presence of climate variability: Lake Tahoe (U.S.A.). Can. J. Fish. Aquat. Sci. **60**: 1452–1461. doi:10.1139/f03-127

Jones, E. M., and others. 2016. Use of remote-sensing reflectance to constrain a data assimilating marine biogeochemical model of the great barrier reef. Biogeosciences **13**: 6441–6469. doi:10.5194/bg-13-6441-2016

Keeler, B. L., S. A. Wood, S. Polasky, C. Kling, C. T. Filstrup, and J. A. Downing. 2015. Recreational demand for clean water: Evidence from geotagged photographs by visitors to lakes. Front. Ecol. Environ. **13**: 76–81. doi:10.1890/140124

Kim, G. E., M. A. Pradal, and A. Gnanadesikan. 2015. Quantifying the biological impact of surface ocean light attenuation by colored detrital matter in an ESM using a new optical parameterization. Biogeosciences **12**: 5119–5132. doi:10.5194/bg-12-5119-2015

Kirk, J. T. O. 1994, *Light and photosynthesis in aquatic ecosystems*. Cambridge Univ. Press.

Klemick, H., C. Griffiths, D. Guignet, and P. Walsh. 2018. Improving water quality in an iconic estuary: An internal meta-analysis of property value impacts around the Chesapeake Bay. Environ. Resource Econ. **69**: 265–292. doi:10.1007/s10640-016-0078-3

Lee, Z. P., K. P. Du, and R. Arnone. 2005. A model for the diffuse attenuation coefficient of downwelling irradiance. J. Geophys. Res.: Oceans **110**: 1–10. doi:10.1029/2004JC002275

Lee, Z. P., A. Weidemann, J. Kindle, R. Arnone, K. L. Carder, and C. Davis. 2007. Euphotic zone depth: Its derivation and implication to ocean-color remote sensing. J. Geophys. Res.: Oceans **112**: 1–11. doi:10.1029/2006JC003802

Lee, Z., S. Shang, C. Hu, K. Du, A. Weidemann, W. Hou, J. Lin, and G. Lin. 2015. Secchi disk depth: A new theory and mechanistic model for underwater visibility. Remote Sens. Environ. **169**: 139–149. doi:10.1016/j.rse.2015.08.002

Lee, Z., S. Shang, L. Qi, J. Yan, and G. Lin. 2016. A semi-analytical scheme to estimate Secchi-disk depth from Landsat-8 measurements. Remote Sens. Environ. **177**: 101–106. doi:10.1016/j.rse.2016.02.033

Lee, Z., S. Shang, K. Du, and J. Wei. 2018. Resolving the long-standing puzzles about the observed Secchi depth relationships. Limnol. Oceanogr. **63**: 2321–2336. doi:10.1002/lno.10940

Long, M. H., J. E. Rheuban, P. Berg, and J. C. Zieman. 2012. A comparison and correction of light intensity loggers to photosynthetically active radiation sensors. Limnol. Oceanogr.: Methods **10**: 416–424. doi:10.4319/lom.2012.10.416

Luckenbach, M. W., R. Mann, and J. A. Wesson. 1999. Oyster reef habitat restoration: A synopsis and synthesis of approaches. Proceedings from the symposium, Williamsburg, Virginia, April 1995. doi:10.21220/V5NK51

Lunt, J., and D. L. Smee. 2014. Turbidity influences trophic interactions in estuaries. Limnol. Oceanogr. **59**: 2002–2012. doi:10.4319/lo.2014.59.6.2002

Mobley, C. D. 2022. The Oceanic Optics Book.

Moore, K. A. 2004. Influence of seagrasses on water quality in shallow regions of the lower Chesapeake Bay. J. Coast. Res. **20**: 162–178. doi:10.2112/si45-162.1

Moore, K. A., R. J. Orth, and D. J. Wilcox. 2009. Assessment of the abundance of submersed aquatic vegetation (SAV) communities in the Chesapeake Bay and its use in SAV management, p. 233–257. *In* X. Yang [ed.], *Remote sensing and geospatial technologies for coastal ecosystems assessment and management, lecture notes in geoinformation and cartography*. Springer-Verlag. doi:10.1007/978-3-540-88183-4_10

Moriarty, J. M., M. A. M. Friedrichs, and C. K. Harris. 2020. Seabed resuspension in the Chesapeake Bay: Implications for biogeochemical cycling and hypoxia. Estuaries Coasts **44**: 103–122. doi:10.1007/s12237-020-00763-8

Najjar, R. G., and others. 2020. Alkalinity in tidal tributaries of the Chesapeake Bay. J. Geophys. Res.: Oceans **125**: e2019JC015597. doi:10.1029/2019JC015597

Newell, R. I. E., J. C. Cornwell, and M. S. Owens. 2002. Influence of simulated bivalve biodeposition and microphytobenthos on sediment nitrogen dynamics: A laboratory study. Limnol. Oceanogr. **47**: 1367–1379. doi:10.4319/lo.2002.47.5.1367

Oestreich, W. K., N. K. Ganju, J. W. Pohlman, and S. E. Suttles. 2016. Colored dissolved organic matter in shallow estuaries: Relationships between carbon sources and light attenuation. Biogeosciences **13**: 583–595. doi:10.5194/bg-13-583-2016

Opdal, A. F., C. Lindemann, and D. L. Aksnes. 2019. Centennial decline in North Sea water clarity causes strong delay in phytoplankton bloom timing. Glob. Chang. Biol. **25**: 3946–3953. doi:10.1111/gcb.14810

Palinkas, C. M., J. M. Testa, J. C. Cornwell, M. Li, and L. P. Sanford. 2019. Influences of a river dam on delivery and fate of sediments and particulate nutrients to the adjacent estuary: Case study of Conowingo Dam and Chesapeake Bay. Estuaries Coasts **42**: 2072–2095. doi:10.1007/s12237-019-00634-x

Pedersen, T. M., K. Sand-Jensen, S. Markager, and S. L. Nielsen. 2014. Optical changes in a eutrophic estuary during reduced nutrient loadings. Estuaries Coasts **37**: 880–892. doi:10.1007/s12237-013-9732-y

Pitarch, J. 2020. A review of Secchi's contribution to marine optics and the foundation of Secchi disk science. Oceanography **33**: 26–37. doi:10.5670/oceanog.2020.301

Preisendorfer, R. W. 1986. Secchi disk science: Visual optics of natural waters. Limnol. Oceanogr. **31**: 909–926. doi:10.4319/lo.1986.31.5.0909

Reay, W. G. 2009. Water quality within the York River estuary. J. Coast. Res. **10057**: 23–39. doi:10.2112/1551-5036-57.sp1.23

Reustle, J. W., and D. L. Smee. 2020. Cloudy with a chance of mesopredator release: Turbidity alleviates top-down control on intermediate predators through sensory disruption. Limnol. Oceanogr. **65**: 2278–2290. doi:10.1002/lno.11452

Sampedro, Ó., and J. R. Salgueiro. 2015. Turbidimeter and RGB sensor for remote measurements in an aquatic medium. Measurement **68**: 128–134. doi:10.1016/j.measurement.2015.02.049

Schwarz, A. M., I. Hawes, and C. Howard-Williams. 1996. The role of photosynthesis/light relationships in determining lower depth limits of Characeae in South Island, New Zealand lakes. Freshw. Biol. **35**: 69–80. doi:10.1046/j.1365-2427.1996.00481.x

Secchi, A., and C. A. Cialdi. 1866. Sul moto ondoso del mare e sulle correnti de esso specialmente auqelle littorali. Cited ONI Transl −655 P 1 Hydrogr. Off. 1955 2nd.: 258–288.

Smith, R. C., and K. S. Baker. 1978. The bio-optical state of ocean waters and remote sensing. Limnol. Oceanogr. **23**: 247–259. doi:10.4319/lo.1978.23.2.0247

Stedmon, C. A., S. Markager, and R. Bro. 2003. Tracing dissolved organic matter in aquatic environments using a new approach to fluorescence spectroscopy. Mar. Chem. **82**: 239–254. doi:10.1016/S0304-4203(03)00072-0

Tait, L. W., F. Thoral, M. H. Pinkerton, M. S. Thomsen, and D. R. Schiel. 2021. Loss of giant kelp, *Macrocystis pyrifera*, driven by marine heatwaves and exacerbated by poor water clarity in New Zealand. Front. Mar. Sci. **8**: 721087. doi:10.3389/fmars.2021.721087

Tango, P. J., and R. A. Batiuk. 2013. Deriving Chesapeake Bay water quality standards. J. Am. Water Resour. Assoc. **49**: 1007–1024. doi:10.1111/jawr.12108

Tarpley, D. R. N., C. K. Harris, C. T. Friedrichs, and C. R. Sherwood. 2019. Tidal variation in cohesive sediment distribution and sensitivity to flocculation and bed consolidation in an idealized, partially mixed estuary. J. Mar. Sci. Eng. **7**: 334. doi:10.3390/jmse7100334

Testa, J. M., V. Lyubchinch, and Q. Zhang. 2019. Patterns and trends in Secchi disk depth over three decades in the Chesapeake Bay estuarine complex. Estuaries Coasts **42**: 927–943. doi:10.1007/s12237-019-00547-9

Tilzer, M. M., N. Stambler, and C. Lovengreen. 1995. The role of phytoplankton in determining the underwater light climate in Lake Constance. Hydrobiologia **316**: 161–172. doi:10.1007/BF00017434

Turner, J. S., P. St-Laurent, M. A. M. Friedrichs, and C. T. Friedrichs. 2021. Effects of reduced shoreline erosion on Chesapeake Bay water clarity. Sci. Total Environ. **769**: 145157. doi:10.1016/j.scitotenv.2021.145157

Turner, J. S., K. A. Fall, and C. T. Friedrichs. 2022. A data repository for clarifying water clarity: A call to use metrics best suited to corresponding research and management goals in aquatic ecosystems (York River estuary case study dataset). William & Mary ScholarWorks. 10.25773/ddh0-x307

Tyler, J. E. 1968. The Secchi disc. Limnol. Oceanogr. **13**: 1–6. doi:10.4319/lo.1968.13.1.0001

USEPA. 2003. Ambient water quality criteria for dissolved oxygen, water clarity and chlorophyll *a* for the Chesapeake Bay and its tidal tributaries. EPA 903-R-03-002

USEPA. 2007. Ambient water quality criteria for dissolved oxygen, water clarity and chlorophyll *a* for the Chesapeake Bay and its tidal tributaries. EPA 903-R-07-005

USEPA. 2008. Ambient water quality criteria for dissolved oxygen, water clarity and chlorophyll *a* for the Chesapeake Bay and its tidal tributaries. EPA 903-R-08-001

Wang, P., L. C. Linker, and R. A. Batiuk. 2013. Monitored and modeled correlations of sediment and nutrients with Chesapeake Bay water clarity. J. Am. Water Resour. Assoc. **49**: 1103–1118. doi:10.1111/jawr.12104

Welschmeyer, N. A. 1994. Fluorometric analysis of chlorophyll *a* in the presence of chlorophyll b and pheopigments. Limnol. Oceanogr. **39**: 1985–1992. doi:10.4319/lo.1994.39.8.1985

West, A. O., J. M. Nolan, and J. T. Scott. 2016. Optical water quality and human perceptions: A synthesis. Wiley Interdiscip. Rev. Water **3**: 167–180. doi:10.1002/wat2.1127

Woodruff, D. L. 1996, *Water clarity of the Neuse River—Pamlico sound estuary, North Carolina: In-situ and remote spectral characterization*. Univ. of North Carolina at Chapel Hill.

Xu, J., R. R. Hood, and S.-Y. Chao. 2005. A simple empirical optical model for simulating light attenuation variability in a partially mixed estuary. Estuaries **28**: 572–580. doi:10.1007/BF02696068

Yard, M. D. 2003. Light availability and aquatic primary production: Colorado River, Glen and Grand Canyons, AZ. Ph. D. Dissertation. Northern Arizona Univ.

Zaneveld, J. R. V., R. W. Spinrad, and R. Bartz. 1980. Optical properties of turbidity standards. Proc SPIE **208**: 159–168. doi:10.1117/12.958272

Zimmerman, R. C. 2003. A biooptical model of irradiance distribution and photosynthesis in seagrass canopies. Limnol. Oceanogr. **48**: 568–585. doi:10.4319/lo.2003.48.1_part_2.0568

Zimmerman, R. C. 2006. Light and photosynthesis in seagrass meadows, p. 303–321. *In* A. W. D. Larkum, R. J. Orth, and C. M. Duarte [eds.], *Seagrasses: Biology, ecology, and conservation ecology*. Springer.

Zimmerman, R. C., V. J. Hill, and C. L. Gallegos. 2015. Predicting effects of ocean warming, acidification, and water quality on Chesapeake region eelgrass. Limnol. Oceanogr. **60**: 1781–1804. doi:10.1002/lno.10139

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