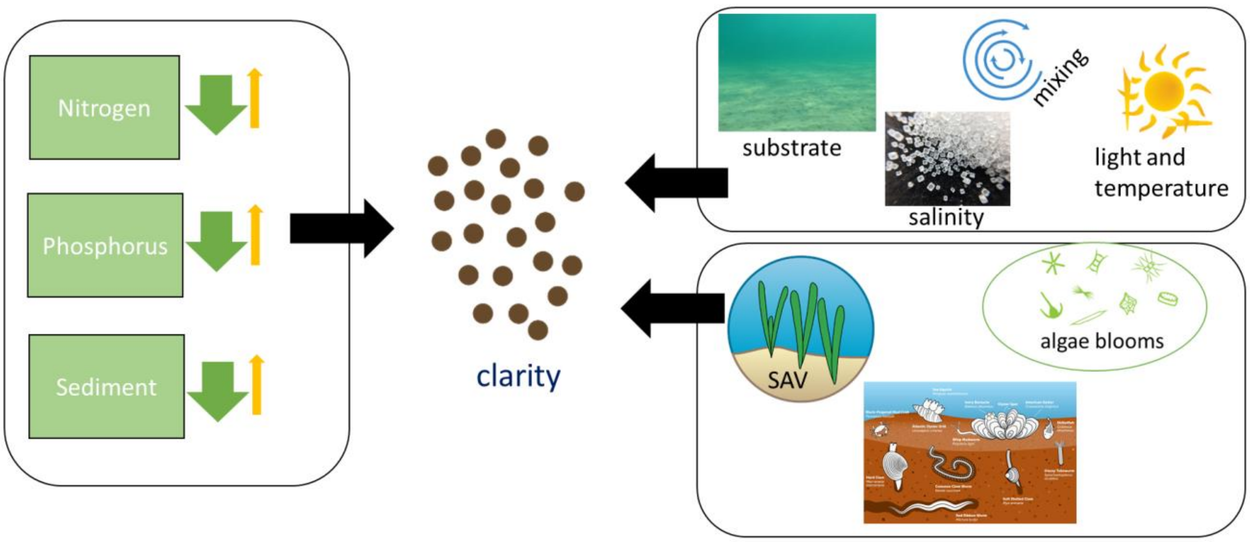
Understanding and Explaining 30 Years of Water Clarity Trends in the Chesapeake Bay's Tidal Waters



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About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in various ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the watershed. For additional information about STAC, please visit the STAC website at www.chesapeake.org/stac.

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Executive Summary

Water clarity is widely recognized as an important indicator of the health and trophic state of aquatic ecosystems and is a key management target given the limit it imposes on the growth of submerged aquatic vegetation (SAV). A better understanding of the controls on water clarity variability may expand our understanding of SAV trends, while providing new insights into the interactions between eutrophication, sediment inputs, and the concentrations and composition of suspended solids. This workshop brought together experts from the multiple disciplines needed to synthesize the current state of the science on water clarity trends and the factors that affect them, and to identify priorities for future research. The group was also asked to address an explicit set of questions posed by the Chesapeake Bay Program in the original STAC workshop proposal. Those questions, along with the group's responses and recommendations for future work, are summarized below.

Why did long-term Secchi depth trends decline from the mid-1980s to present day, despite reductions in both point- and nonpoint- source nutrient loads from the watershed?
From 1985-2016, of a total of 130 stations, 9 (7 percent) of stations showed a significant improvement in Secchi depth, 55 (42 percent) of stations saw a significant degradation, and 66 (51 percent) of stations showed no significant trend. Over the same period of time, below fall line wastewater treatment plant nitrogen loads declined by about 60 percent (44 million pounds per year), or about 10-18 percent of total loads. However, reductions from major wastewater treatment plant upgrades were highly localized, and inter-annual flow variability still dominated load patterns overall. Optical modeling of trends in Secchi depth suggest that since 1985 there has been a shift in the nature of suspended solids in the Bay mainstem toward smaller, more highly organic particles that favor shallower Secchi depths. The relationship between dominant suspended particle types and nutrient inputs requires additional study.

Why have we seen a different story with light attenuation trends (i.e., water clarity as K_d, measured with radiometers)?
Light attenuation data are not available to the same temporal extent as the Secchi data, but a comparison of consistent time periods shows that while Secchi trends were degrading at the majority of the stations from the 1990s to early 2000s, most of the K_d data showed either no trend or improving trends. In recent years, however, the trends have been more consistently improving for both measures. The reason for these differences is likely because Secchi depth and K_d measures are different representations of water clarity. The spectral sensitivity of the human eye differs substantially from that of instruments used to measure light attenuation. Secchi depth is a measure of how far into the water the human eye can discern an object – something akin to cloudiness - while K_d is a measure of light attenuation. This difference may explain the different associations observed between Secchi depth, K_d, and water column components such as total suspended solids (TSS) and chlorophyll-*a*. Contrasting trends in Secchi depth and K_d may indicate that the variety of components that affect water transparency and light attenuation are responding to different drivers, and/or are responding to changes in different ways. For example, an increase

in abundance of smaller, more organic-rich suspended particles may have affected K_d less than it affected Secchi. However, insufficient empirical observations of inorganic suspended solids (ISS) and organic suspended solids (OSS) concentrations across time still hinder our understanding of the dynamics driving temporal patterns in transparency and light attenuation.

Why have mainstem Secchi depth trends begun to improve in the last decade?
From 2007-2016, improving Secchi depth trends were observed more broadly across the Bay's long-term monitoring network than for longer-term trends, particularly along the mainstem Bay. Management-driven nutrient reductions may have played a role, however several consecutive years of average or below-average river flows into the Bay may also have been a major driver of improving trends. A preliminary analysis showed that, when adjusted for river flow or salinity, improving Secchi depth trends disappeared in some (but not all) locations. These results suggest that Secchi depth improvements are related to lower flows in some regions, but that there are also areas of the Bay where Secchi depth may be improving independent of variation in flow or salinity, perhaps in response to the cumulative effects of improved watershed management.

What has more impact on trends in water clarity: internal resuspension of particulate matter, or sediment inputs from the watershed and local shoreline?
Our current understanding of the relative impacts of internal and external sources of suspended solids requires refinement. On monthly time-scales, variation in Secchi depth co-varies most significantly with in-water properties, such as TSS, chlorophyll-a, and colored dissolved organic matter (CDOM), while Bay-wide responses to riverine input are typically weak. Over interannual scales, however, Secchi depth does broadly respond to freshwater input. One must also consider how drivers vary regionally. For example, statistical analyses have shown that sediment and nutrient loads can play a significant role in water clarity in tidal fresh portions of the mainstem and tributaries. However, in downstream waters with high wave or tidal energy and in naturally turbid regions (i.e., the estuarine turbidity maximum), internal resuspension appears to be more important. In the middle and lower Bay, bankloads and internal production have also been found to be more important than watershed runoff as sources of suspended solids. The decreasing influence of watershed sediment inputs in more saline waters may be due to high sinking rates and trapping of sediment in floodplains and tidal freshwater wetlands. While on average, sediment loads from the watershed decrease as one moves downstream, intense storms can provide large pulses of sediment that have a substantial transient impact on water clarity, and that can transport sediment to the lower estuary in extreme cases.

What about biology? Some local improvements in water clarity have been linked to bivalve population explosions and to the resurgence of SAV communities. When degraded water clarity recovers sufficiently to support dense SAV beds, their presence has been shown to further enhance transparency. While substantial, the direct effect of algal blooms on water clarity is transient. Some analyses of Chesapeake Bay chlorophyll-*a* monitoring data have suggested that living phytoplankton biomass is presently not on average a major direct cause of light attenuation in the Bay. However, phytoplankton may play an indirect role in long-term water clarity patterns through their contribution to more diffuse and long-lasting concentrations of organic detritus and to increased CDOM. Analysis of CDOM measurements indicate that it is presently a significant cause of light attenuation in the Bay. A conceptual framework defining several distinct "water clarity habitats" within the Bay emerged from synthesis discussions, with the idea that controls on water clarity vary depending on habitat characteristics.

Current management strategies aim to improve Chesapeake Bay water quality (including water clarity) by reducing nitrogen, phosphorus, and sediment inputs to tidal waters (Chesapeake Bay Program 2019). Does this approach target the appropriate drivers of poor water clarity?

Management strategies that reduce nutrient inputs should improve water clarity via feedbacks with phytoplankton and SAV communities. Strategies that reduce contemporary riverine sediment inputs may have a direct effect on water clarity in tidal fresh regions, while indirectly improving water clarity more broadly by reducing inputs of sediment-bound nutrients. Controlling local shoreline erosion may have long-term as well as transient beneficial effects locally, particularly in embayed habitats. However, control through shoreline armoring negatively affects transport of coarse sediments that are necessary for beaches and seagrass. Bivalve restoration efforts can have dramatic impacts if populations exceed a critical threshold (Phelps 1994, Goldman 2007). Tradeoffs between promoting bivalve restoration and SAV restoration should be factored into management strategies.

Knowledge gaps and research recommendations

- Recent efforts in applying statistical modeling to test hypotheses need to be continued, and insights from them should be integrated with the Chesapeake community's process models.
- The sources of suspended organic matter and its concentration relative to inorganic solids in tidally influenced waters need to be better characterized and understood, including their responses to riverine discharge and salinity.
- Better data on phytoplankton biomass, microbial processing of suspended organic matter, and CDOM production in estuarine environments are needed to better understand the response of water clarity to biological processes and associated feedback mechanisms.
- A great deal of potential remains untapped in regard to eliciting new insights from currently available data. For example, the focus to date has been more on mid-channel long-term data. New work should include analysis of available data on shallow water properties.
- The idea that the relative strengths of different drivers vary across water clarity "habitats" is not an established paradigm; rather it is a set of hypotheses that need to be tested within and across environmental settings.

In addition to producing the following workshop report, the water clarity synthesis effort produced two peer-reviewed journal articles to date (Zhang and Blomquist 2017, Testa et al. 2019), with an additional workshop-inspired journal article (Buchanan 2019) in review. The synthesis effort was summarized in a session at the 2018 Chesapeake Research and Modeling Symposium (ChesRMS), and materials contributed to a poster at the Fall 2018 American Geophysical Union Meeting.

Introduction

Workshop Purpose

Water clarity is widely recognized as an important indicator of the health and trophic state of aquatic ecosystems and is a key management target given the limit it imposes on the growth of submerged aquatic vegetation (SAV). Observations and analyses in the years leading up to this workshop indicated that water clarity as measured by Secchi disk depth had remained low or continued to decline from the 1980s to the 2000s across much of the Bay's tidal habitats despite declining nutrient and sediment loads. At the same time, it appeared that water clarity as light attenuation (K_d) had improved. As the workshop approached, evidence was emerging that Secchi depth had also begun to improve in recent years, although it remained below levels seen in the 1980s. The persistence of low Secchi depths despite stable or declining nutrient and sediment loads from at least some regions of the Bay's watershed, the contrasting trends in K_d, and the more recent improvements in Secchi depth, all highlight the complexity of biological and physical processes that influence underwater light in estuaries. A better understanding of the controls on water clarity variability may expand our understanding of SAV trends, while providing new insights into the interactions between eutrophication, sediment inputs, and the concentrations and composition of suspended solids.

This workshop brought together experts from the multiple disciplines needed to synthesize the current state of the science on water clarity trends and the factors that affect them, to communicate the implications of existing insights for management, and to identify priorities for future research. The workshop was divided into two parts. Part I, held in February 2017, focused on summarizing the current state of knowledge and how to advance science to answer the CBP Partnership's questions. Part II, held in May 2017, was an opportunity for participants to share their research progress, to integrate their insights findings on physical, biological, and biogeochemical interactions, and apply these insights to address the needs outlined by the CBP in its workshop proposal. Specifically, participants brought their expertise to bear on the following questions:

- Why did long-term Secchi depth trends decline from the mid-1980s to present day, in spite of reductions in both point- and nonpoint- source nutrient loads from the watershed?
- Why have we seen a different story with light attenuation trends (i.e., water clarity as K_d, measured with radiometers)?
- Why have mainstem Secchi depth trends begun to improve in the past decade?
- What has more impact on trends in water clarity: internal resuspension of particulate matter, or sediment inputs from the watershed and local shoreline?
- Current management strategies aim to improve Chesapeake Bay water quality (including water clarity) by reducing nitrogen, phosphorus, and sediment inputs to tidal waters (Chesapeake Bay Program 2019). Does this approach target the appropriate drivers of poor water clarity?

Workshop Format

Though the proposal followed a traditional STAC workshop format, this workshop was reorganized in order to support a synthesis effort. To do so, activities were conducted through several phone calls and two 2-day workshops. During these in-person workshops, a subset of participants was actively engaged in analysis, and an additional group of subject-matter experts provided presentations and participated in discussions. The ultimate goals of this effort were to integrate existing and new findings, to address the questions posed by the Chesapeake Bay Program in the workshop proposal, and to identify critical research needs to advance our ability to explain water clarity trends.

Synthesis Effort Summary

Part I: September 2016 – January 2017

Over the course of five conference calls between September 2016 and January 2017, the group:

- Identified a list of research questions for advancing our ability to explain observed water clarity trends;
- Identified a set of new analyses that could be conducted with existing data and resources;
- Decided on a "3-pronged approach" to synthesizing the current state of knowledge comprising reviews of:
    - (1) Mid-channel water clarity findings;
    - (2) Processes and feedbacks especially important to shallow water clarity;
    - (3) Trends in loads from the watershed relevant to estuarine water clarity.

The following research activities were initiated:

- Joel Blomquist (USGS) and Qian Zhang (UMCES-CBPO) began analyses to characterize sediment, chlorophyll-*a*, and organic carbon inputs from the River Input Monitoring (RIM) stations;
- Jeremy Testa (UMCES), Slava Lyubchich (UMCES), and Qian Zhang (UMCES) began analysis of the effects of sediment and nutrient loads from the watershed on water clarity;
- Carl Friedrichs (VIMS) conducted an in-depth synthesis of the existing state of science on Chesapeake Bay water clarity constituents, including how they are measured and changing patterns over time.

Specific activities, decisions, and research questions are summarized in the agenda and introductory presentation for Workshop 1, included in Appendix A of this report.

The first face-to-face workshop took place on February 6-7, 2017 at the UMCES Chesapeake Biological Laboratory. On the morning of Day 1, Jeni Keisman (USGS) introduced the structure and goals of the workshop and Richard Batiuk (EPA) then described his motivation for submitting the workshop proposal, the topic's importance to the Chesapeake management community, and its relevance to the Total Maximum Daily Load (TMDL) Midpoint Assessment. The morning was rounded out by a presentation from Carl Friedrichs summarizing his synthesis of the existing understanding of Chesapeake water clarity constituents and patterns.

After lunch, Jeff Cornwell (UMCES) and colleagues described their current understanding of processes and feedbacks of particular importance to clarity in shallow waters. Qian Zhang and Joel Blomquist then presented an overview of long-term fluxes and trends of riverine inputs to the Chesapeake Bay relevant to water clarity (Zhang and Blomquist 2018). In addition to traditional constituents (nitrogen, phosphorus, sediment), they expanded their analysis to include fine sediment, chlorophyll-*a*, and organic carbon.

The remainder of Workshop I consisted of robust discussion identifying and debating the relative importance of a variety of physical and biological processes in determining the clarity of Chesapeake tidal waters. A rough conceptual model began to take shape, postulating that the Bay can be categorized into several habitats based on physical characteristics, across which the relative importance of different factors varies.

Part II: February 2017 – May 2017

Over the course of three conference calls between February and May, the concept of a habitat classification matrix was refined, and Greg Noe (USGS) gave an invited webinar on "Sediment delivery from the watershed to the Chesapeake Bay: the *Sediment Shadow* in tidal freshwater rivers." Chuck Gallegos (SERC) reported on his communications with the South River Federation regarding the development of a total suspended solids (TSS) TMDL for the South River, as well as their implementation of restoration projects to mitigate sediment loading.

Day 1 of the Part II workshop was organized into sections covering the following: results of new analyses completed since the February workshop; presentations on the current understanding of biological controls on/interactions with water clarity; and a summary of options for calculating residence times to classify bay waters into water clarity habitats. Rebecca Murphy (UMCES) presented her work quantifying more than 30 years of Secchi depth and K_d trends using Generalized Additive Models (GAMs). Jeremy Testa presented his work with Slava Lyubchich and Qian Zhang to associate trends in Secchi depth with TSS, chlorophyll-*a* concentrations, and nutrient and sediment loading from the USGS River Input Monitoring (RIM) stations of the nine major Chesapeake Bay tributaries. Claire Buchanan (ICPRB) presented a conceptual model of phytoplankton-water clarity relationships, and Dan Dauer (ODU) summarized the current understanding of how benthic bivalve and non-bivalve benthic communities affect and interact with sediment and water clarity. Jeni Keisman provided a comparison of residence-time estimation models with potential to inform habitat classification in the Bay.

Day 2 began with an invited presentation by Grace Brush (JHU) on historical sediment delivery to the Bay, followed by a brief recap of previous presentations by Noe, Zhang and Blomquist, and a discussion of the influence of sediment loads on water clarity trends relative to internal drivers.

The workshop wrapped up with a return to the questions originally proposed by the CBP, and a discussion of the degree to which our work has and can address managers' priorities.

Current Recommendations for Managing Water Clarity

After reviewing the topics presented and discussed during the face-to-face meetings and conference calls, the group returned to the questions originally proposed by Rich Batiuk and listed in the introduction of this report. Explanations and recommendations are summarized below.

Why did long-term Secchi depth (i.e., water transparency) trends decline from the mid-1980s to present day, despite reductions in both point- and nonpoint- source nutrient loads from the watershed?

Analysis of trends in Secchi depth across the Bay's long-term monitoring network conducted by Rebecca Murphy showed that from 1985-2016, 7 percent of stations showed a significant improvement in Secchi depth, 42 percent of stations saw a significant degradation, and 51 percent of stations showed no significant trend in Secchi depth. Over the same period of time, below fall line wastewater treatment plant nitrogen loads declined by about 60 percent (44 million pounds per year), or about 10-18 percent of total loads. However, reductions from major wastewater treatment plant upgrades were highly localized, and inter-annual flow variability still dominated load patterns overall. Optical modeling of trends in Secchi depth (Gallegos et al. 2011) suggest that since 1985 there has been a shift in the nature of suspended solids in the Bay mainstem toward smaller, more highly organic particles that favor shallower Secchi depths. The relationship between dominant suspended particle types and nutrient inputs requires additional study. The prospect that a nutrient reduction threshold exists, which must be reached before appreciable water clarity improvements occur, was discussed.

Why have we seen a different story with light attenuation trends (i.e., water clarity as K_d, measured with radiometers)?

The spectral sensitivity of the human eye differs substantially from that of instruments used to measure light attenuation, thus Secchi depth and K_d measures are different representations of water clarity. Secchi depth is a measure of how far into the water the human eye can discern an object - something akin to cloudiness - while K_d is a measure of light attenuation. These differences may explain the different associations observed between Secchi depth, K_d, and water column components such as TSS and chlorophyll-*a*. In the literature synthesis conducted by Carl Friedrichs, K_d was shown to be more strongly related to TSS than to chlorophyll-*a*. New analysis conducted by Jeremy Testa and Slava Lyubchich showed that the association of Secchi depth with TSS and/or chlorophyll-*a* is location-dependent (Testa et al. 2019). Contrasting trends in Secchi depth and K_d may indicate that the variety of components that affect water transparency and light attenuation are responding to different drivers, and/or are responding to changes in different ways. Optical modeling from the literature suggests that ISS in the mid-to-lower Bay decreased from 1985 to 2005, whereas OSS increased. This caused Secchi depth to degrade over this period even though K_d improved (Gallegos et al. 2011, Harding et al. 2016). Friedrichs et al. (2018) presented a simplistic theoretical model that assumes that since ~2006, both ISS and OSS have tended to decrease. These assumed temporal changes in the relative concentrations of ISS and OSS since ~2006 are able to qualitatively reproduce observed improvements in both K_d and Secchi. However, insufficient empirical observations of ISS and OSS concentrations across time still hinder our understanding of the dynamics driving temporal patterns in transparency and light attenuation.

Why have mainstem Secchi depth trends begun to improve in the last decade?

From 2007-2016, improving Secchi depth trends were observed more broadly across the Bay's long-term monitoring network than for "long-term" (i.e., 30+ year) trends, particularly along the mainstem Bay. Twenty-six percent of stations showed a significant improvement in Secchi depth in the more recent period (up from 7 percent); 16 percent showed degrading water clarity (down from 42 percent), and there was no significant trend at 58 percent of monitoring locations. Management-driven nutrient reductions may have played a role, however, there was consensus within the group that several consecutive years of average or below-average river flows into the Bay may also have been a major driver of improving trends. Even without mitigation efforts, years with less precipitation have lower nutrient loads relative to rainier years. A preliminary analysis conducted by Rebecca Murphy (Murphy and Keisman 2018) showed that, when adjusted for river flow or salinity, improving Secchi depth trends in some – but not all – locations disappeared. In other words, these results suggest that Secchi depth improvements are related to lower flows in some regions, but that there are also areas of the Bay where Secchi depth may be improving independent of variation in flow or salinity – perhaps in response to the cumulative effects of improved watershed management. Additional investigation is needed to better understand how the relative concentrations of ISS and OSS are related to river flow and salinity, and thus, how river flow and salinity ultimately influence the optical response of Secchi depth versus $K_{d.}$

What has more impact on trends in water clarity: internal resuspension of particulate matter, or sediment inputs from the watershed and local shoreline?

Our current understanding of the relative impacts of internal and external sources of suspended solids requires refinement and varies across environmental settings within the Bay. On monthly time scales, variation in Secchi depth co-varies most significantly with in-water properties, such as TSS, chlorophyll-a, and CDOM, while Bay-wide responses to riverine input are typically weak (Testa et al. 2019). Over interannual scales, however, Secchi depth does broadly respond to freshwater input (Harding et al. 2016). One must also consider how drivers vary regionally. For example, statistical analyses have shown that sediment and nutrient loads can play a significant role in water clarity in tidal fresh portions of the mainstem and tributaries (Zhang et al. 2013, Zhang et al. 2015, Testa et al. 2019). However, in downstream waters with high wave or tidal current energy and in naturally turbid regions (i.e., the estuarine turbidity maximum), internal resuspension appears to be more important (Curry et al. 2007, Shi et al. 2013, Testa et al. 2019). In the middle and lower Bay, Cerco et al. (2013) also found bankloads and internal production to be more important sources of suspended solids relative to watershed runoff.

The decreasing influence of watershed sediment inputs in more saline waters may be due to high sinking rates (Sanford et al. 2001, Palinkas et al. 2014), and trapping of sediment in floodplains and tidal freshwater wetlands. Tidal rivers can trap large quantities of sediment between the head-of-tide and mouth of the estuary, depositing sediment in both channel and wetlands, leading to meaningful reductions in sediment loading to estuaries (Meade 1982, Downing-Kunz and Schoellhamer 2015, Ralston and Geyer 2017). This phenomenon, which has been called the 'sediment shadow' (Ensign et al. 2015), refers to the lower sediment availability observed in tidal freshwater areas of rivers when compared to contiguous nontidal and oligohaline reaches of the same river. Sediment loads from watersheds can be trapped at large rates by nontidal floodplain deposition and river channel storage downstream of watershed nontidal loading gages (Noe and Hupp 2009), as well as by tidal freshwater forested wetlands (TFFW) located downstream of the head-of-tide (Ensign et al. 2015, 2016). As a result, much of the sediment load has been reduced to low levels in lower tidal freshwater rivers downstream of these sedimentation hotspots.

While on average, sediment loads from the watershed decrease as one moves downstream, intense storms can provide large pulses of sediment that have a substantial transient impact on water clarity, and that can transport sediment to the lower estuary in extreme cases. A combination of monitoring and modeling of the impact of Hurricane Isabel (2003) on the York River suggested that post-storm freshwater flows pushed the turbidity maximum downstream, resulting in sediment transport to the lower York estuary (Gong et al. 2007). Turbidity levels along the tidal York River spiked on the first day of landfall but returned to pre-storm conditions within 30 hours at most stations. However, tidal fresh stations experienced moderately elevated turbidity levels for several days following the storm (Reay and Moore 2005). In 2011, freshwater flows associated with Tropical Storm Lee interacted with the Coriolis force to transport fine-grained sediments down the western shore of the mainstem to waters south of the West and Rhode rivers. Elevated turbidity in the mid-bay lagged peak Susquehanna flows by four days and remained elevated for several days after that (Palinkas et al. 2014).

What about biology?

Some local improvements in water clarity have been linked to bivalve population explosions and to the resurgence of SAV communities. Two examples of improved water clarity coincident with bivalve population increases have been documented in Chesapeake Bay. The first occurred between 1979 and 1992 in the tidal fresh portion of the Potomac River, near Washington D.C. The Asiatic clam species *Corbicula fluminea* was first observed in the late 1970s during benthic community surveys, after which its population increased dramatically to a peak of about 4 kg/m^2 in 1984, after which it declined just as rapidly. This population explosion corresponded with a substantial decline in phytoplankton abundance and increase in water clarity, followed by a resurgence of SAV beginning in 1983. As *C. fluminea* biomass declined from 1986-1992, so did water clarity and SAV abundance (Cohen et al. 1984, Phelps 1994). The second case involved a population explosion of the native mussel *Mytilopsis leucophaeata* in the waters of Old Man Creek, a tributary of the Magothy River. Coincident with this increase, water clarity in the creek measured the clearest that it had been in over a decade of monitoring (Goldman 2007 in Chesapeake Quarterly 6(2) pp 4-11).

At landscape scales, SAV-water clarity effects in the Chesapeake Bay region have been found to vary, with wide and dense stands and tall canopies of SAV showing the greatest effects on reduced turbidity and increased light penetration (Gruber and Kemp 2010, Gruber et al. 2011, Gurbisz et al. 2016). When degraded water clarity recovers sufficiently to support dense SAV beds, their presence has been shown to attenuate wave energy, reduce water column nutrient concentrations, and increase the settling rate of suspended solids; all functions that further enhance transparency. These effects vary seasonally, with maximum impacts observed during periods of peak biomass (Gruber and Kemp 2010). Their strength is also related to their capacity to affect a large proportion of the overlying water column in relatively shallow depths at which SAV are found (Ward et al. 1984, Moore 2004, Adams et al 2016, Gurbisz et al. 2016).

Phytoplankton communities can affect water clarity directly, as a component of particulate organic matter (POM), or indirectly, as their exudates are an internal source of dissolved organic matter (DOM) in the Chesapeake Bay (Keller and Hood 2011, Buchanan, *in review*). The importance of phytoplankton biomass in long-term water clarity patterns is a topic of debate. Clarity-reducing algal blooms occur every year in the Chesapeake Bay (Tango et al. 2004), and where their occurrence overlaps with SAV beds they can negatively affect SAV abundance (Gallegos and Bergstrom 2005). While substantial, the direct effect of algal blooms on water clarity is transient. Some analyses of Chesapeake Bay chlorophyll-*a* monitoring data have suggested that phytoplankton biomass is presently not, on average, a major direct cause of light attenuation in the Bay. However, phytoplankton may play an indirect role in long-term water clarity patterns through their contribution to more diffuse and long-lasting concentrations of organic detritus and to increased CDOM. Analysis of CDOM measurements indicate that it is presently a significant cause of light attenuation in the Bay (Xu et al. 2005). There is evidence to suggest that Secchi depth decreases are correlated to increasing proportions of chlorophyll-*a* in some regions, particularly in the lower Bay (Testa et al. 2019). There is also some evidence that the presence of mycrophytobenthos (e.g., algal mats) may stabilize the sediment surface. However, results are mixed, and effects may follow a cyclical pattern as mature algal mats become more susceptible to bottom shear (Porter et al. 2004).

The water clarity habitats concept

The following conceptual diagram, which emerged from workshop discussions, proposes several "water clarity habitats" within which different factors play dominant roles in controlling water clarity patterns.

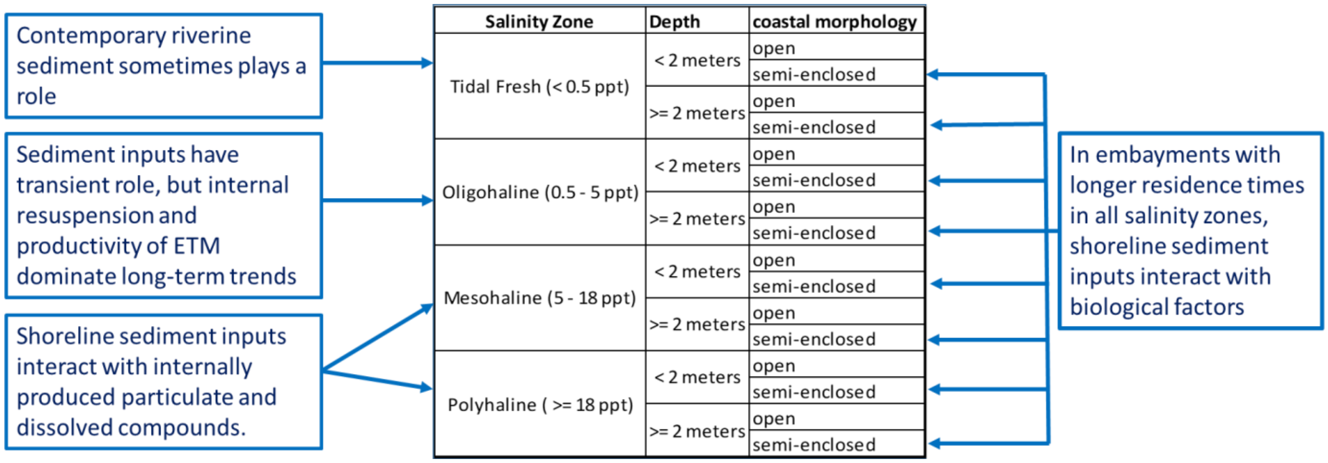

Figure 1: Proposed "water clarity habitats" framework for exploring drivers of water clarity across environmental settings in Chesapeake Bay and its tidal tributaries

Current management strategies aim to improve Chesapeake Bay water quality (including water clarity) by reducing nitrogen, phosphorus, and sediment inputs to tidal waters (Chesapeake Bay Program 2019). Does this approach target the appropriate drivers of poor water clarity?

- Management strategies that reduce nutrient inputs should improve water clarity via feedbacks with phytoplankton and SAV communities.
- Strategies that reduce contemporary riverine sediment inputs may have a direct effect on water clarity in tidal fresh regions.
- Sediment input controls reduce sediment-bound nutrient inputs.
- Contemporary sediment inputs from high discharge events have at least a transient effect on water clarity; sediment controls that target high discharge events could improve this.
- Controlling local shoreline inputs/erosion may have long-term as well as transient beneficial effects locally, particularly in embayed habitats. However, control through shoreline armoring negatively affects transport of course sediments that are necessary for beaches and seagrass.
- Bivalve restoration efforts might have dramatic impacts if populations can exceed a critical threshold.
- Tradeoffs between promoting bivalve restoration and SAV restoration should be factored into management strategies.

Knowledge gaps and research recommendations

- Recent efforts in applying statistical modeling to test hypotheses need to be continued, and insights from them should be integrated with the Chesapeake community’s process models.
- The sources of suspended organic matter and its concentration relative to inorganic solids in tidally influenced waters need to be better characterized and understood, including their responses to riverine discharge and salinity.

- Better data on phytoplankton biomass, microbial processing of suspended organic matter and CDOM production in estuarine environments are needed to better understand the response of water clarity to biological processes and associated feedback mechanisms.
- A great deal of potential remains untapped with regard to eliciting new insights from currently available data. For example, the focus to date has been more on the mid-channel long-term data. New work should include analysis of available data on shallow water properties.
- The concept of the relative strengths of different drivers across water clarity "habitats" is not an established paradigm; rather it is a set of hypotheses that need to be tested within and across environmental settings.

2018 Chesapeake Community Research and Modeling Symposium (ChesRMS) Session

Findings from the Water Clarity Synthesis were presented in a session at the Chesapeake Community Research and Modeling Symposium (ChesRMS), held in Annapolis, MD on June 12-14, 2018. In addition to presentations by workshop participants, the session included some independent contributions from other Chesapeake researchers. Presentations and authors are listed below. Abstracts are included in the Symposium's full program, published online at http://www.chesapeakemeetings.com/ChesRMS18/CompleteProgramr.pdf.

Water Clarity in Chesapeake Bay: trends, drivers, and research priorities. Session at the 2018 Chesapeake Community Research and Modeling Symposium. Jeni Keisman and Carl Friedrichs, co-leads. Presentations:

- Barletta, Stephanie. Suspended sediment variability in the surface layer of upper Chesapeake Bay
- Friedrichs, Carl, Keisman, J. Describing and explaining Chesapeake Bay water clarity: a literature review.
- Moriarty, Julia, Friedrichs, M., Harris, C.K. Effects of seabed resuspension on primary productivity and remineralization in Chesapeake Bay.
- Porter, Elka, Johnson, B.J., Sanford, L.P. Effect of hard clam, *Mercenaria mercenaria*, density and bottom shear on sediment erodibility.
- Zhang, Qian, Blomquist, J.D. Watershed export of fine sediment, organic carbon, and chlorophyll-a to Chesapeake Bay: spatial and temporal patterns 1984-2016.
- Testa, Jeremy, Lyubchich, S., Zhang, Q. Patterns and trends in Secchi Disk depth over three decades in the Chesapeake Bay estuarine complex.
- Murphy, Rebecca, Keisman, J. Comparison of Secchi depth and K_d trends while adjusting for freshwater input variations.
- Deluca, Nicole M., Zaitchik, B. F., Curriero, F. C. Can multispectral information improve remotely sensed estimates of total suspended solids? A statistical study in the Chesapeake Bay.
- Keisman, Jeni, Friedrichs, C., Buchanan, C., Batiuk, R., Blomquist, J.D., Cornwell, J., Lane, M., Lyubchich, S., Moore, K., Murphy, R., Noe, G., Orth, R., Porter, E., Sanford, L., Testa, J., Trice, M., Zhang, Q., Zimmerman, R. Examining trends in water clarity in the Chesapeake Bay: a synthesis of findings from recent STAC workshops.

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Appendix A: Workshop Agendas

STAC Workshop:

Understanding and Explaining 30+ Years of Water Clarity Trends in the Bay's Tidal Waters

February 6-7th, 2017

University of Maryland Center for Environmental Science
Chesapeake Biological Laboratory
Bernie Fowler Laboratory Building
142 Williams St, Solomons, MD 20688

10:00 am **Coffee and light Breakfast at UMCES-CBL**

10:30 am **Workshop Introduction –** *Jeni Keisman (USGA)*
How did we get here?
3-pronged approach
Workshop goals

10:40 am **Motivation for the synthesis –** *Rich Batiuk (EPA-CBPO)*
Batiuk will give an opening introductory presentation on motivation for this synthesis, the importance of explaining trends in water clarity, and relevance to the TMDL Midpoint Assessment.

Synthesis Presentations – Current State Of The Science (40 minute presentation; 20 minutes for discussion)

11:00 am **Synthesis: Understanding of Chesapeake Bay Water Clarity Patterns -** *Carl Friedrichs (VIMS), Peter Tango (USGS), Jessie Turner (VIMS), Marjy Friedrichs (VIMS), Rebecca Murphy (UMCES), and others TBD*

12:00 pm **Catered Lunch at UMCES-CBL**

1:00 pm **Synthesis: Processes and feedbacks especially important to shallow water clarity –** *Jeff Cornwell (UMCES), Larry Sanford (UMCES), Chuck Gallegos (SERC), Elka Porter (UBALT)*

2:00 pm **Synthesis: Long-term Riverine Inputs from the Major Tributaries to Chesapeake Bay Relevant to Water Clarity –** *Qian Zhang (UMCES-CBPO), Joel Blomquist (USGS)*

This presentation will provide a synthesis of long-term fluxes and trends of riverine inputs to Chesapeake Bay that are relevant to water clarity, including traditional constituents (namely, suspended sediment, total phosphorus, and total nitrogen) and additional constituents (namely, fine sediment, chlorophyll-a, and organic carbon). Conceptual models on the interconnections between these inputs and estuarine water clarity will be presented and discussed.

3:00 pm **Afternoon Break**

3:15 pm **Group Discussion – Key messages from "Current State" Syntheses** *-All*

4:15pm **Day 1 Wrap-Up, Goals for Day 2, Dinner Plans**

5:15pm **Recess**

<u>Day Two</u>

8:30 am **Light Breakfast at UMCES-CBL**

9:00 am **Discussion and Agreement on Key Messages from Current State of Knowledge; Guiding Future Work** *(All)*

10:00 am **Break**

New Analysis Presentations – Moving the Science Forward

10:15 am **Linking fall-line sediment and chlorophyll-a inputs to estuarine water clarity** *– Jeremy Testa (UMCES-CBL), Slava Lyubchich (UMCES-CBL), Qian Zhang (UMCES-CBPO)*

11:30 am **Break (Boxed Lunches Provided)**

12:00 pm **"Working Lunch" Group Discussion (All)**

1. **Next Steps**
2. **Plans for Part II of the Workshop (Spring 2017?)**
3. **Communication of results**
    a. **Report/White Paper/Product**

1:00 pm **Adjourn**

Questions Raised

- Which measure of light availability – secchi depth or K_d – do SAV and algae respond to?
- Aside from oysters, do benthic organisms in Chesapeake Bay package sediment into large (fast-settling) biodeposits?
- What are temporal and spatial patterns in (concentration? biomass?) of small organic particles in Bay's surface waters?
- What is the source of small organic particles in Chesapeake Bay? Can they be characterized?
- How have benthic communities changed over time? What is the potential for changes in benthic communities to have affected filtering capacity?
- How has phytoplankton community composition changed over time?
- Have TSS, turbidity, and secchi depth changed in similar ways in different regions of the bay?
- Has there been a turnaround in the product of K_d and secchi in the past 5-6 years? Can the product of K_d and secchi be used as a proxy for particle-type change over time?
- Do temporal trends in any/all of the following correlate with trends in water clarity:
- Sediment particle size distribution; sediment loads; chlorophyll *a* loads; water temperature; phytoplankton community composition; benthic community composition
- Are temporal trends in mid-channel water clarity consistent with temporal trends in near- shore, shallow-water clarity?
- Why do we see/not see improvements in water clarity in certain places where we do/don't expect responses? Examples include the Back R. where there have been massive WWTP improvements, and the Chester River where column particulates have crashed and SAV is abundant.

Scientific and Technical Advisory Committee (STAC) Workshop: Understanding and Explaining 30+ Years of Water Clarity Trends In the Bay's Tidal Waters

Part II - May 2-3, 2017

Galway Room, O'Callaghan Annapolis Hotel, 174 West Street, Annapolis, MD 21401
http://www.chesapeake.org/stac/workshop.php?activity_id=269

Tuesday, May 2

9:30 am	Breakfast and Coffee (Provided)
10:00 am	Introductions, Schedule, Goals – *Jeni Keisman (USGS)*
10:15 am	Draft Report Structure and Content Themes: Physical Setting; Water Quality; Biology; Sediment

Estuarine Biogeochemistry Controls and Interactions

10:30 am	GAM Trends in Secchi Depth and Kd – *Rebecca Murphy (UMCES)*
11:00 am	Latest Results from New Water Clarity Analyses – *Jeremy Testa (UMCES-CBL) and Slava Lyubchich (UMCES-CBL)*

Biological Controls and Interactions

11:30 am	Phytoplankton Conceptual Diagram and Some Phytoplankton-Water Clarity Relationships – *Claire Buchanan (Interstate Commission on the Potomac River Basin)*
12:00 pm	The Role of Benthic Communities in Water Clarity Trends – *Dan Dauer (ODU)*
12:30 pm	Lunch (Provided)

Integration: Water Clarity Trends, Water Quality

1:30 pm	Discussion of Linkages between Rebecca Murphy's Water Clarity Trends and Jeremy Testa and Slava Lyubchich's Findings
2:00 pm	Side Meetings/Breakouts

Environmental Setting/Physical Controls

3:00 pm	Summary of Options for Residence Time Estimate Models – *Jeni Keisman (USGS)*
3:30 pm	Habitat Classification Effort: Latest Matrix, Methods and Locations Selected for Classification Analysis

4:00 pm Break

Integration Discussion: Estuarine Water Quality, Biological Controls, Sediment Controls

4:15 pm Integration Discussion, Part I (teaser to set up for more discussion on Day 2)

How do our understandings of estuarine biogeochemical controls, phytoplankton dynamics, and sediment influxes, fit together into a conceptual model that informs the observed temporal and spatial patterns in water clarity shown by Rebecca Murphy's work?

5:00 pm Recess

<u>Wednesday, May 3</u>

8:30 am Breakfast and Coffee (Provided)

9:00 am Goals for Day

9:15 am Feedback on Day 1 – *Rich Batiuk (EPA)*

9:30 am Side Meetings/Breakouts

10:30 am Break

10:45 am Historical Sediment Delivery to Chesapeake Bay – *Grace Brush (JHU)*

11:15 am Brief Recap of Qian Zhang's Results from Part 1 and Greg Noe's Webinar

11:30 am Discussion: Conceptual Model of Sediment's Influence on Water Clarity Trends (External vs. Internal? Transient vs. Long-Term?)

12:00 pm Lunch (Provided)

12:30 pm Integration Discussion, Part II

How do our understandings of physical setting, estuarine biogeochemical controls, biological controls, and sediment controls, fit together into a conceptual model that informs the observed temporal and spatial patterns in water clarity shown by Rebecca Murphy's work?

1:30 pm Emerging Hypotheses (Follow Up on Integration Discussion)

2:00 pm Revisit Managers' Priorities: How well does our work align?

2:30 pm Wrap-Up, Next Steps:

- What are we covering?
- What's missing?
- How does our work address Rich Batiuk's priorities?
- Action items. Commitments. Deadlines. Fall Workshop.

3:00 pm Adjourn

Appendix B: Workshop Participants

Part I: February 6-7, 2017

Name	Affiliation	Contact
Ball, Bill	CRC	ballw@chesapeake.org
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Part II: May 2-3, 2017

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