Advancing Monitoring Approaches to Enhance Tidal Chesapeake Bay Habitat Assessment for Submerged Aquatic Vegetation, Water Clarity, Chlorophyll *a* and Dissolved Oxygen

STAC Workshop Report
Virtual
May 11, 2022
April 22, 2022
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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 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 http://www.chesapeake.org/stac.

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Brooke Landry, Maryland DNR. *Heteranthera dubia* in clear water on the
Potomac River, 2019.

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Executive Summary

Water quality monitoring capacity has been declining for the Chesapeake Bay Program (CBP) at a time when information needs are growing, and existing data gaps must be addressed to provide critical decision-support for managers. The CBP Scientific Technical Assessment and Reporting Team (STAR) led a Principal's Staff Committee requested gap analyses toward understanding support needed to increase water quality monitoring capacity. Advanced technologies and alternative monitoring and assessment approaches in the form of satellite-based measurements, continuous water quality in-situ sensor arrays, and community science efforts offer a growing portfolio of opportunities for expanding data collections and analysis program capacities. However, implementations of these options into elements of Chesapeake Bay water quality monitoring programs have been limited. Where new technologies have been adopted (e.g., shallow water continuous water quality monitoring), such temporally rich data streams have supported Bay health insights yet had limited use in regulatory water quality criteria assessment.

This Scientific Technical Advisory Committee (STAC) supported workshop provided an appropriate forum for engaging our CBP partnership regarding the maturity of new and evolving monitoring and analysis capacities to address program information needs while acknowledging limitations with adopting new tools and approaches. Improving natural resources monitoring efficiency and effectiveness could expand the scientific and technical foundations for making robust, strategic choices on decisions for CBP Partnership community-based priorities, policies, and management actions.

Workshop findings and recommendations demonstrate progress in science, technology, and analyses addressing long-standing programmatic limitations in data collection and analysis capacities. State-of-the-science updates highlighted in the workshop span the spectrum of efforts representing improvements, successes, remaining challenges toward operationalizing protocols, and guidance toward research, or adoption and implementation by monitoring programs.

Findings and Recommendations

Overall: Advanced water quality and living resource monitoring and analysis methods are actively progressing toward new or updated assessment protocol options that are suitable for CBP monitoring program adoption and operational use. However, the workshop results show that the variation in maturity of new method applications is evolving at different paces depending on the parameter of interest. Satellite-based submerged aquatic vegetation (SAV) cover assessments including artificial intelligence and machine-learning (AI/ML)-supported image interpretation represent the most mature method developments. At the other end of the spectrum, satellite-based water clarity assessments are feasible at bay-wide scales but have limitations due to a paucity of calibration and verification data. Adoption of any new method or protocol can be expected to require a period of comparison study where old and new approaches may require coincident financial support while achieving community support for making programmatic changes.

Session summaries with specific findings are provided below on the State of the Science for advances in monitoring for Chesapeake Bay SAV, water clarity, dissolved oxygen (DO), and chlorophyll *a*.

Session 1. Advanced monitoring approaches to enhance tidal Chesapeake Bay habitat assessment for Submerged Aquatic Vegetation

Fixed wing aircraft-based aerial imagery has provided the CBP with consistent annual, bay-wide SAV cover survey data since 1985; roots of the program and its cover assessment protocol pre-date the formation of the CBP. Coincidentally, spatial resolution of satellite-based imagery has increased, and satellite-based imagery has become more publicly available via image libraries; however, resolutions of the most often available imagery (i.e., tens to hundreds of square meters) were not comparable to the standard sub-meter resolution of the aircraft aerial imagery. More recently, high resolution satellite imagery (approximately sub-10m^2) has been increasingly publicly available as a potential data resource. Gaps in completing the annual Chesapeake Bay SAV cover survey have occurred when weather or water conditions affected access to survey tracks or because of limitations imposed for national security reasons when surveying habitat adjacent to military installations.

Present research has demonstrated advances in our opportunities for operationalizing a monitoring scheme with satellite-based programming 1) at potentially lower cost with freely available satellite imagery, 2) at bay-wide scale, 3) across all seasons, 4) across all salinity zones, 5) at high spatial resolution, 6) with the observational power to use daily to sub daily image collection, 7) also resolving historical aerial image data collection limitations due to national security when working around military installations and 8) adopting the use of new interpretive algorithms (i.e., Support Vector and Convolutional Neural Network algorithms) are performing similarly on classification with the Dove PlanetScope image interpretation. A present constraint on the use of PlanetScope imagery for monitoring involves coordinating with them on image charges. Efforts to develop a data-sharing relationship between PlanetScope and the U.S. Government are underway.

Submerged Aquatic Vegetation – Recommendations

- Continue to acquire satellite imagery to supplement the annual aerial image-based SAV cover assessment; however, focus on gap areas where restricted air-space access makes aerial image acquisition difficult.
- Scale up the local level proof-of-concept work to the regional scale with satellite-based imagery and algorithm-supported characterization of SAV cover.
- Expand temporally the proof-of-concept with regional scale SAV cover evaluation to a full SAV season assessment to demonstrate successful operation and maintenance of new protocols (e.g., a spring season mesohaline region SAV assessment).
- Develop the automation software supporting the SAV cover assessment workflow from image acquisition through image classification to the generation of usable biogeochemical output products.
    - Included in this work would be

    - 1) the need to eliminate training on each image
    - 2) reducing misclassification of SAV cover in pixels using water quality flags for high turbidity, colored dissolved organic matter (CDOM), or other relevant parameters, and
    - 3) applying a repeated pixel classification approach from multiple scenes to eliminate single pixel SAV classification errors.
- Tuning of the steps in the process to take imagery like PlanetScope from data acquisition through SAV cover product development are needed. This includes creating documentation of the new, frequency-of-detection-based methods of SAV cover from satellite image interpretation, addressing sparse area cover mapping, and ensuring atmospheric correction with new imagery.
- Compare product development results of Random Forest and Convoluted Neural Network approaches.
- Develop a method to translate pixel-based results of commercial satellite image characterization into vector-based SAV bed area delineations in order to align outputs that include bed area and bed density consistent with historical assessment methods; coincidentally developing a rasterized version of historical aerial imagery that demonstrates to the Chesapeake Bay management community cover alignment between satellite-based and aerial fixed-wing based SAV cover acreages could be used to align historical and new approaches for tracking SAV cover response to management actions.
- Add calibration and verification field sites to further support the accuracy of our survey such as establishing sentinel sites. Sites should represent the diversity of key habitats to inform and benefit algorithm tuning and long-term understanding of shifts in species distributions and changes in SAV community composition.
- Work across agencies with satellite imagery companies to better understand the factors controlling image acquisition at needed locations and times for more effective use of satellite resources for Chesapeake Bay SAV monitoring purposes.
- Assuming protocol development for satellite-based SAV cover assessment is achieved, publish protocols as community supported and U.S. Environmental Protection Agency (EPA) approved methods for reference in habitat assessment by jurisdictions.

Session 2. Advanced monitoring approaches to enhance tidal Chesapeake Bay habitat assessment for Water Clarity and Chlorophyll *a*.

Water Clarity

State of the science research demonstrated water clarity characterization can be evaluated over bay-wide scales using satellite-based resources with published interpretive algorithms. However, consistent monitoring of water clarity with satellite-based resources remains a work in progress. Limitations to accuracy are presently a function of limited calibration and verification data across diverse habitats in the tidal waters of the bay. A network of calibration and verification sites is needed representing diverse habitats in Chesapeake Bay to create more robust evaluations of water clarity and reduce uncertainty in clarity classifications supporting future status and trend assessments. The guidance provided in the workshop suggests 1) using the best measurement for your specific research or management needs/goals, and 2) validating the measurement that is most needed.

Water clarity – Recommendations

- Sustain existing long-term water quality monitoring and shallow water monitoring program efforts that already provide the foundations for calibration and verification of satellite data products.
- Establish a network of calibration and verification sites for K_d measures, operating during the SAV growing season at a minimum, and expand to year-round (considering changing environmental conditions on growing season duration). Locate the monitoring sites to represent diverse, shallow water habitats of the optically complex tidal waters in Chesapeake Bay to support robust calibration of satellite resources.
- Evaluate newer satellite image sources for improving water clarity assessment accuracy and spatial resolution
- Additional research to tune and improve existing, published algorithms for interpreting water clarity from satellite-based data or creating new algorithms that increase accuracy beyond existing algorithm characterizations of available satellite-based data resources.

Chlorophyll

Advances in remote sensing of chlorophyll continue to improve. Research shows that a chlorophyll *a* condition assessment can be generated using satellite-borne sensor data and support interannual environmental change assessments at medium to high resolution at the bay-wide scale. Examples of satellite-derived time series for chlorophyll *a* condition in Chesapeake Bay have been published or are in the process of being published offering the opportunity to consider peer-reviewed approaches for adoption into monitoring program protocols for long-term habitat condition assessments. Advances highlighted in the workshop with satellite-based data are using government owned and operated satellites for bay-wide chlorophyll condition assessments. Data access to these satellite data are cost-free, which minimizes the challenges associated with incorporating satellite-based monitoring into annual budgets for any water quality monitoring program. Advances in Harmful Algal Bloom (HAB) species detection with satellite-based resources aligned with ground truthing efforts are evolving for Chesapeake Bay which can enhance the utility of satellite-based products for water quality assessments.

Chlorophyll a – Recommendations

- Sustaining existing long-term monitoring and shallow water monitoring program efforts is critical to continue providing robust calibration and verification of evolving satellite data products.
- Given the groundbreaking work to develop annual bay-wide chlorophyll characterization with consistent protocols across decades, support is needed for work through workshop, action team or other venue bringing researchers, analysts, and managers together to align needs and expectations for a viable bay-wide, quantitative chlorophyll criteria assessment protocol using satellite-based data resources.
- HAB characterization from satellite-based assessment is needed to translate the existing Chesapeake Bay narrative criteria that applies to waters without quantitative criteria such that narrative criteria can expand the basis of quantitative assessment support from the

outputs related to HAB metrics (i.e., frequency, magnitude, duration, timing and distribution/spatial extent).
- Upon completion of protocol development for satellite-based chlorophyll *a* assessment, submit documentation with CBP community support for EPA approval and publication of methods to serve as reference to the management community on habitat assessment.

Session 3. Advanced monitoring approaches to enhance tidal Chesapeake Bay habitat assessment for Dissolved oxygen.

Advanced monitoring and assessment approaches are necessary to fully assess water quality standards attainment in all 92 segments of Chesapeake Bay. Dissolved oxygen criteria attainment assessment is particularly limited by a lack of high temporal frequency water quality data collection in open and deep waters to address short-duration criteria (i.e., 7-day mean, 1-day mean, instantaneous minimum). New vertical sensor arrays that are robust, portable, and more cost-effective than previously tested designs were successfully pilot tested on the open waters of Chesapeake Bay during 2019 and 2020. The new arrays can collect the necessary high temporal frequency salinity, temperature and dissolved oxygen data from open-water deployments to support habitat and criteria assessment at durations and temporal density rarely available until now. The infrastructure is designed to address a monitoring gap recognized in the CBP program since 2003 to support dissolved oxygen criteria assessment across all applicable time scales (i.e., instantaneous to 30-day mean). Dissolved oxygen criteria assessment is built around living resource needs making the data and analyses directly aligned with fish and shellfish habitat assessment needs.

Research on four-dimensional (4D) habitat assessment has matured in the scientific literature since the findings of 2008 STAC panel report (Curriero et al. 2008) which indicated that techniques were not yet available to address the challenges of building and supporting a 4D water quality interpolator. A Generalized Additive Model (GAM) solution to the challenge of 4D interpolation was featured in this workshop. The pilot of a GAM 4D interpolator over a major region of the mainstem Chesapeake Bay has been successful at the scale of daily mean application. Reducing uncertainty, scaling up to bay-wide application, and integrating new high temporal density data streams, and incorporating short-term variability in dissolved oxygen measures are development steps identified for moving forward and completing the Phase 1 tool outlined in the workshop.

Dissolved oxygen – Recommendations

- A study design is needed for distribution of stations for habitat assessments that includes fixed and rotating stations in accordance with habitat assessment requirements (e.g., 3-year assessments in each segment for dissolved oxygen criteria attainment assessment support)
- At least one vertical array should be outfitted with sensors at 1-m depth intervals to serve as a reference
- Complete and implement use of the 4D interpolator to support DO criteria and other habitat assessments for the tidal waters of Chesapeake Bay

- Complete and implement a 10-array system of fixed and mobile stations that support bay-wide assessment through a rotating distribution of infrastructure
- Sustain existing long-term monitoring and shallow water monitoring program efforts that provide spatial and temporal coverage in habitats to support 4D interpolator-based habitat assessment products.
- Upon completion of community supported protocol development and assessment, provide documentation for EPA approval and publication of the proposed methods to serve the community as a published reference for the methods.

Introduction

Workshop Objectives and Purpose

This workshop aimed to highlight state-of-the-science findings for evolving water quality monitoring approaches. The primary workshop objective was to develop actionable recommendations on adaptive monitoring and assessment for consideration in developing the next generation CBP tidal water quality monitoring program. Adaptation will need to occur with methods that 1) increase temporal density in water quality data collections to address the full spectrum of conditions defining living resource life cycle needs (i.e., instantaneous minimum with dissolved oxygen to seasonal means with chlorophyll and annual maximum extents with water clarity/SAV), 2) increase spatial resolution to provide information needs on spatial variability in water quality and represent diverse tidal water habitats, 3) increase efficiency and cost-effectiveness associated with data collections to expand the information return on data collection investment, 4) advance water quality assessment efficiency and effectiveness using applications of new, intelligent algorithms applied to interpreting diverse data collection sources (e.g., aerial imagery and satellite-derived data), and 6) updating Bay habitat assessment tools (e.g., the Bay Interpolator) for more effectively using diverse data sources to improve habitat characterization at all management-relevant temporal and spatial scales addressing cross-cutting decision-support needs of CBP Goal Teams (GTs).

Management Relevance

EPA, in collaboration with hundreds of scientists, managers and policymakers across the CBP partnership, published its ambient water quality criteria for dissolved oxygen, water clarity and chlorophyll. Criteria targets represent conditions supporting survival, growth, and reproduction of aquatic life, characterizing restoration conditions for Chesapeake Bay habitat (USEPA 2003). These target conditions have been adopted by Bay jurisdictions for tidal water quality standards and define success for a restoration goal as a function of achieving the Chesapeake Bay Total Maximum Daily Load (TMDL) (USEPA 2010).

The traditional CBP partnership's long-term water quality monitoring and assessment program was deemed "marginal" for measuring and reporting on all published criteria (i.e., criteria parameters are dissolved oxygen, water clarity/SAV and chlorophyll *a*) used to produce an accounting of Bay health (USEPA 2003). Since 2003, the traditional monitoring program has been sustained with some modifications, and there are published analysis options to measure all criteria in all applicable seasons (e.g., USEPA 2017). However, the community has never achieved assessment of habitat at all the temporal and spatial scales necessary for full annual and seasonal accounting to provide a full health report for ANY of the 92 segments in the tidal bay and sub-estuaries. The monitoring program has been insufficient in meeting data needs to effectively monitor and assess all required water quality criteria in all designated uses associated with water quality standards the Bay jurisdictions. As such, information needed for diverse CBP partner interests (e.g., Water Quality GT, Sustainable Fisheries GT, Healthy Habitats GT, STAR-Climate Resiliency Workgroup) on habitat conditions across management-relevant temporal and spatial assessment scales has had significant gaps. A Multi-metric Water Quality Standards Indicator was developed to use the limited information available from the monitoring program to estimate conditions where data gaps existed in the accounting until more complete accounting could be supported by more appropriate monitoring data and assessment protocols (Hernandez-Cordero et al. 2020).

Increased monitoring capacity is needed to expand the Chesapeake Bay long-term water quality monitoring program with scientifically sound, cost-effective decisions. Additional capacities must address the nearly 2-decade long short-comings of the CBP's traditional monitoring and assessment program in meeting management expectations for decision support. Data and assessment needs include addressing 1) short duration (instantaneous, 1-day mean and 7-day mean) dissolved oxygen measurements in all tidal bay habitats, 2) greater spatial representation and resolution of habitat conditions, 3) cost-effective measurement methods that maximize the utility of the number of data points in space and time per dollar invested, and 4) bay-wide water quality estimation in four dimensions that uses traditional and new data streams to inform estimates of habitat status. Formalizing integration of new data streams and new protocols for interpretation into the analysis and reporting of bay conditions is essential to growing the capacity of our water quality monitoring networks. Modernizing our monitoring program capacity and related assessment tools will generate updated outputs providing information needs outlined by CBP teams addressing the Water Quality Goal, Climate Resiliency Goal, Sustainable Fisheries Goal and Healthy Habitat Goal of the 2014 Watershed Agreement (CBP 2014). Subsequent statements of science needs that can benefit from analysis and reporting capacities targeted during this workshop are outlined under the Chesapeake Bay Programs Strategy Review System (SRS) process by these groups and have been captured in the CBP Strategic Science and Research Framework science needs database accessible using the following link: https://star.chesapeakebay.net/Need/About .

Why a STAC Workshop? Urgency and Time Relevance

The traditional long-term water quality monitoring and assessment program supported through the CBP partnership remains world class with the existing resources; however, 1) there have been 20 years of incomplete measurement and reporting on attainment of water quality criteria that EPA published and bay jurisdictions adopted into their water quality standards designed to protect Bay habitats and living resources, 2) traditional Chesapeake Bay monitoring programming capacity for obtaining data used in habitat assessment protocols has eroded for over a decade, and 3) with no new funding available for the last decade to expand the traditional monitoring program, and to sustain any new investments, cost effective options are needed. Working with new data sources and data streams that are increasingly available such as community science-based datasets, satellite-based imagery, or high temporal density continuous water quality data from previously challenging habitats to maintain such monitoring infrastructure represent capacity building opportunities for the program.

Recognizing existing capacity limitations on sustaining and growing CBPs monitoring programs, during the Water Quality Standards Attainment and Monitoring outcome SRS presentation to the Management Board in July 2020, Scientific, Technical Assessment and Reporting (STAR) leadership requested increased collaboration between STAC and STAR to address gaps in capacity. Opportunities for capacity building in cooperation with the Chesapeake Bay science and management community were outlined as:

- Adopting data from non-traditional monitoring sources (e.g., Community Science) into assessments.

- Incorporating data from new technologies into assessments.
- Updating analysis approaches to accommodate new data sources.
- Updating decision protocols for evaluating analysis results.

This STAC workshop provided a forum for engaging our CBP partnership in support of formalizing the use of alternative data sources and interpretive tools within the framework for the traditional long-term water quality monitoring program for enhanced decision-support. Workshop presentations and community input with inform synthesis on the status, successes, and limitations of using approaches beyond the traditional long-term water quality monitoring data collection of the CBP and habitat assessment protocols through the next generation Bay water quality interpolator. Results of this workshop are anticipated to provide science-based support for modernizing the CBP water quality monitoring and assessment program. Updating our approaches involved in tidal Bay water quality monitoring and assessment will expand the scientific and technical foundations for making strategic changes for more effective Bay restoration now and into the future.

Workshop Format

Our workshop was organized to address four topic areas within three sessions between December 2021 and May 2022. Sessions were conducted as 1-day virtual events:

> Session 1. Advanced monitoring approaches to enhance tidal Chesapeake Bay habitat assessment. Submerged Aquatic Vegetation, December 9, 2021, workshop webpage.
>
> Session 2. Advanced monitoring approaches to enhance tidal Chesapeake Bay habitat assessment. Water clarity and Chlorophyll *a,* April 22, 2022, workshop webpage.
>
> Session 3. Session 3. Advanced monitoring approaches to enhance tidal Chesapeake Bay habitat assessment. Dissolved oxygen, May 11, 2022, workshop webpage.

Agendas were organized to start each day with an overview of the overall workshop framework followed by objectives of the specific session. Three to four feature presentations were slated with experts providing present habitat assessment methods, then state-of-the-science updates were provided on advanced data collection methods, product development, and application for characterizing habitat conditions in the tidal Chesapeake Bay. Following the opening session technical review, workshop participants presented details on a range of subjects related to the workshop topics (e.g., data availability, data acquisition, data storage, data interpretation methods). Most importantly, ample time was reserved for discussion each day during all three sessions.

Each of the four session topics has had recent peer-reviewed publications highlighting the power of one or more new approaches to potentially address bay-wide habitat assessments with increased spatial resolution, temporal frequency, or both. These advances in data collection, interpretation, and product development offered consideration for investment toward operationalizing the approaches as a CBP partnership monitoring program element. Participants in each session were asked to provide insight and consideration into integrating new technology and methods showcased in the workshop into our monitoring programming regarding issues that have limited investment or adoption to date:

- Method cost
- Spatial coverage
- Temporal frequency of location coverage
- Image resolution
- Habitat considerations
- Satellite continuity and historical data comparability

Participants in each session were further surveyed to provide context for recommendation development that would describe what was needed to overcome any remaining hurdles between the state of the research and its opportunity for adoption and operational use in the Chesapeake Bay monitoring programming. Consistent themes included research, monitoring, and management needs.

Workshop Results

Submerged Aquatic Vegetation

Session 1. Advanced monitoring approaches to enhance tidal Chesapeake Bay habitat assessment Submerged Aquatic Vegetation, December 9, 2021.

Advanced Monitoring Focus: Overview of Chesapeake Bay SAV Acreage Assessment

Since 1984, the Chesapeake Bay Program has worked with the Virginia Institute of Marine Science (VIMS) to conduct an annual survey of (SAV) throughout the Chesapeake Bay and its tidal waters. The Chesapeake Bay SAV Monitoring Program (hereafter the SAV monitoring program) collects, interprets, and synthesizes both aerial imagery and ground survey data to report SAV acreage and density throughout the Bay annually and reliably and is the most successful and consistent large-scale, long-term SAV monitoring program in the world. SAV scientists and managers across the Chesapeake Bay watershed have grown to depend upon the data for a variety of purposes, from basic research and education to regulatory decision-making to annual public communications on the health of the Chesapeake Bay ecosystem. Like many large-scale and long-term monitoring efforts, the SAV monitoring program has experienced difficult periods and stressed to sustain funding necessary to maintain a fully operational program. Avenues for ensuring the longevity and growth of the program to achieve its full vision continue to be explored.

In response to chronic budgetary concerns over the last decade, alternative monitoring approaches were evaluated during The CBP partnership's SAV Aerial and Ground Survey Design Workshop, coordinated by the CBP's SAV Workgroup, and held on March 29th, 2017, in Annapolis, MD. Based on responses to a comprehensive SAV data user questionnaire distributed in advance of the workshop and input from participants during the workshop, three alternative design options for the aerial survey were identified for further exploration including using satellite-based imagery.

An opportunity to begin exploring the use of high spatial resolution commercial satellite imagery (CSI) for the SAV monitoring program occurred in 2018 when 26% of the Bay remained unmapped for the summer's Bay-wide aerial survey. The data gaps prompted VIMS analysts to explore alternative imagery from their regular aerial image data collection for use in completing the 2018 assessment. The 2018 data gaps were significantly reduced using alternative aerial imagery, publicly available satellite imagery, and private commercial-satellite imagery (CSI). Successful use of the CSI prompted the question of full-scale applicability of satellite resources for use in conducting the annual SAV surveys. The question of applicability was developed into a CBP STAC workshop proposal by Brooke Landy (Maryland Department of Natural Resources (MD DNR)) and Peter Tango (U.S. Geological Survey (USGS)) in 2019.

CBP STAC supported a 2020-2021 workshop that focused solely on satellite integration opportunities with SAV monitoring, *Exploring Satellite Image Integration for the Chesapeake Bay SAV Monitoring Program* (Landry et al. 2021). This STAC Advanced Monitoring Workshop committee recognized that substantive research progress was made in a short period of time and addressed recommendations developed in the recent satellite image integration workshop. The rapid research progress warranted a full session in this workshop involving the researchers from the past workshop to provide updates evaluating 1) progress on implementing satellite image acquisition protocols with CSI), 2) advances in SAV characterization of high resolution commercial satellite imagery, 3) AI/ML algorithm development for satellite image interpretation, and 4) lessons learned from the VIMS-led protocol test on Maxar satellite tasking and calibration to evaluate feasibility and implications of the exercises for moving the Chesapeake Bay Program toward a satellite-based SAV monitoring program for tidal waters of the Chesapeake Bay.

Presentation Summaries for the Submerged Aquatic Vegetation Session

Explanation of Overall Advanced Monitoring Workshop Purpose and Intent — *Peter Tango (USGS)*


Advancing Monitoring Approaches to Enhance Assessment Water Quality Standards for Chesapeake Bay Dissolved Oxygen, Water Clarity/SAV and Chlorophyll a Criteria
Workshop Event 1 Focus: Status of advances in SAV assessment
Chair: Peter Tango USGS@CBPO
STAC Staffer: Meg Cole
Subcommittee: Tish Robertson VADEQ, Brooke Landry MD DNR, Bill Richardson USEPA, Breck Sullivan USGS

Figure 1. *Slide from Session 1. Presentations can be found on the session webpage.*

The basis of the workshop had its foundations in an ongoing request for help needed to address CBP water quality monitoring program capacity shortfalls. During 2020, monitoring capacity gaps were identified and expressed by STAR to the Management Board during a Strategic Review System presentation. The gaps were translated to needs and documented in the STAR-coordinated Science Needs Database during STARs Strategy Review System summary presentation. The work needed by the science and management community to expand monitoring capacity to meet decision-support expectations in data collections formed an outline of what would be addressed in this workshop:

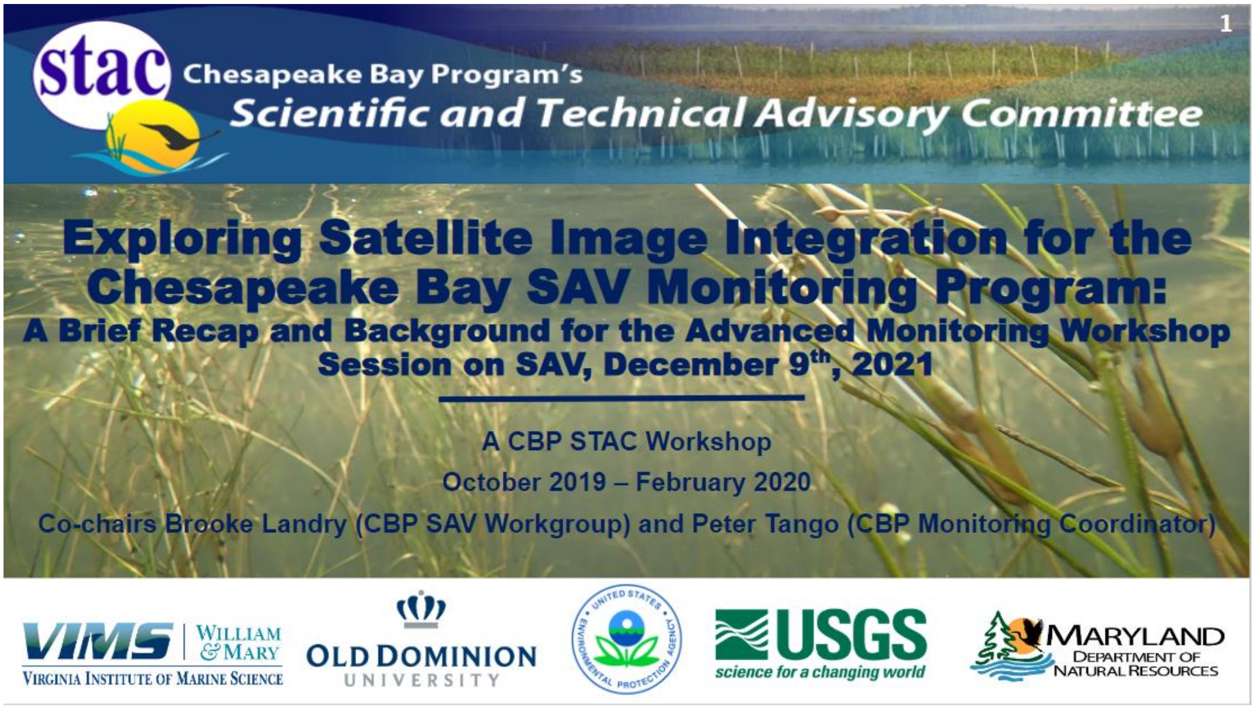
> "Request for STAC and STAR to work with the Bay science and management community to extend monitoring capacity through the commitment to:
> - adopting data from non-traditional monitoring sources into assessments
> - incorporating data from new technologies into assessments
> - updating analysis approaches to accommodate new data sources, and
> - update decision protocols for evaluating analysis results"

Substantial progress has been made integrating new technologies and approaches toward generating data and improving assessments of key water quality criteria parameters of interest to the CBP: DO, SAV, Water Clarity, and chlorophyll a. Significant research advances to support greater efficiency and effectiveness in water quality and SAV monitoring are evident in publications since that last major CBP monitoring program review (i.e., MRAT 2009). An essential summary question to be answered for the overall workshop was: *Do recent advances in the fields of monitoring and assessment provide readily adoptable support for addressing information gaps, improving analyses, and offer cost-effective, sustainable solutions to support water quality standards attainment assessments in Chesapeake Bay?*

Objectives of SAV Session and brief review of the FY19 STAC SAV Satellite Workshop —

Brooke Landry (MD DNR)

Steering Subcommittee member Brooke Landry (MD DNR) led the SAV session.



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stac Chesapeake Bay Program's

Scientific and Technical Advisory Committee

Exploring Satellite Image Integration for the Chesapeake Bay SAV Monitoring Program:

A Brief Recap and Background for the Advanced Monitoring Workshop Session on SAV, December 9th, 2021

A CBP STAC Workshop

October 2019 – February 2020

Co-chairs Brooke Landry (CBP SAV Workgroup) and Peter Tango (CBP Monitoring Coordinator)

VIMS William & Mary Virginia Institute of Marine Science

Old Dominion University

United States Environmental Protection Agency

USGS science for a changing world

Maryland Department of Natural Resources

Figure 2. *Slide from Session 1. Presentations can be found on the session webpage.*

The Chesapeake Bay SAV Monitoring Program is the most successful large-scale, consistent, long-term SAV monitoring program in the world. Bay-wide SAV data are used for state water quality criteria assessments and tracking progress toward SAV goal attainment, aquaculture site evaluations and permitting decisions, detection and tracking of Bay-wide SAV violations (i.e., propeller scarring), shoreline structures, alteration, and erosion control, permitting decisions, and peer-reviewed science. To increase the program's long-term sustainability in the face of growing difficulties, the overarching purpose of the workshop was to determine if High-Resolution Commercial Satellite Imagery (CSI):

- Can be obtained and processed in a more efficient and cost-effective manner than aerial imagery collected from fixed-wing aircraft.
- Can provide imagery of sufficient quality and spatial cover to monitor SAV populations throughout Chesapeake Bay.
- Can provide a route to automated processing using ML algorithms and AI.

During the 2020-21 workshop, it was determined that acquiring high-resolution CSI at no cost to the local agency is an option under the existing license agreement between the National Geospatial-Intelligence Agency (NGA) and contracted commercial sources. The basic premise of the agreement is that any federal agency that requires satellite imagery from contracted commercial sources can request and obtain said imagery at no cost to the local agency; 2018 updates to the Water Resource Development Act (P.L. 115-270), which amends Section 117 of the Clean Water Act (CWA), called for the EPA to carry out an annual SAV survey in Chesapeake Bay. This constitutes a requirement and makes CBP eligible for no-cost CSI.

Resolution, orbital paths, tasking capacity, and tilting capacity all vary among and between public and private satellites based on their specific missions. WorldView 3 (owned by Maxar) was determined to have the most appropriate satellite constellation for the purposes of the Chesapeake Bay SAV Monitoring Program and was the satellite option focused on during the workshop.

If acquisition of usable data and imagery is achieved, the resolution has been deemed adequate for hand-delineation of SAV beds in Chesapeake Bay. Further, the existing license agreement allows tasking requests at specific times over specific areas for images to be collected. There is an expansive archive of CSI collected from the satellite mission to browse at this time; however, many of the images are not suitable to support CBP monitoring needs, i.e., obscured by cloud cover, collected during turbid conditions, or collected during high tide or off-season. Tasking for image acquisition on specific days and under specific conditions is possible working with private satellite imagery companies using capacities outlined in the existing license agreement. Tasking provides a satellite-based monitoring approach that aligns with historical SAV assessments using fixed-wing aircraft surveys. However, tasking is cumbersome, time-consuming, and has been shown to be relatively unreliable because there is no guarantee that the request for a time-date-location for an image will be prioritized and acquired in the overall workflow.

CSI publication and retention are also complicated. The imagery belongs to a private source company. Permission and licensing are required to publish each image, and permission is not guaranteed. However, derived products (i.e., SAV maps) are not subject to this licensing requirement, and EPA primarily needs the derived maps and acreage values to develop and provide annual SAV cover updates under the CWA. Furthermore, State agencies need the original data, i.e., the original imagery, to provide transparency, such as in the review of aquaculture lease applications and permitting decisions.

Rapid progress is occurring with the application of AI algorithms to image characterization for uses such as SAV cover classification and accounting. Algorithms/AI/machine learning will likely eventually allow for automation of SAV cover mapping; however, at this time, there is substantial remaining work to do before algorithms are ready for use in addressing diverse water quality conditions found across Chesapeake Bay. With funding and present rate of progress, workshop participants estimated that Bay-specific algorithm developments could be ready in 3-5 years. Interestingly, using AI may yield more precise results than the historical analysis methods but may skew long-term trends. The current method of hand delineation can create bed boundaries by joining clumps to form SAV patches, whereas AI based accounting at this time would only count the clumps, excluding the sparse or unpopulated space in between patches. An analysis need going forward is to bring results from the two methodologies into alignment.

The 2020-21 STAC workshop steering committee recommended that VIMS conduct the contracted aerial acquisition of the Bay SAV that has supported the annual tracking assessment needs alongside a CSI tasking exercise in a calibration study. The tasking exercise was intended to task the contracted company with image data collection over the entire Chesapeake Bay within the SAV growing season of one year to mimic the existing aerial survey approach. This back-up assessment would be used to evaluate the likelihood of acquiring all the data necessary for a full Bay SAV assessment using satellite-based resources. A calibration exercise was further intended to determine if use of the satellite images could produce similar results to the aerial imagery-derived survey results. This work was funded by EPA following the STAC workshop.

Wilcox and Patrick (2022) demonstrated the challenges of acquiring a full set of desired shallow water tidal Bay survey imagery. Wilcox and Patrick (2022) further indicated analysis of suitable of clear imagery within the set if images acquired provided comparable local SAV cover assessments using methods applied to interpreting the traditional fixed-wing aircraft acquired imagery.

Quantification of Blue Carbon Burial in Seagrass Ecosystems from High Resolution Commercial Imagery — *Victoria Hill (ODU)*; Presentation Slides

Using PlanetScope (San Francisco, CA) SuperDove high resolution CSI, a process was presented illustrating satellite image classification for a pixel-based SAV cover assessment. The process refines the images after the initial classification protocol is completed, then uses multiple images of the same area over the course of a season to create a frequency of encounter raster for SAV presence. SAV presence over time, by pixel, is used to compute SAV density. SAV density results are being translated into carbon storage. This work demonstrates the advances made in high resolution CSI processing and the synthesis of seasonal image collections over an area to produce SAV density maps on the way to assessing blue carbon; the CBP uses SAV density maps developed by VIMS (through the long-term aerial survey program) to generate the annual indicator for SAV cover in tidal waters of Chesapeake Bay.) These advances move our community closer to a viable resource assessment protocol using CSI suitable for seasonal SAV cover assessment and additional uses. High fidelity of the project site SAV assessments with VIMS survey results was demonstrated in the pilot project areas. Alignment between the two data collection and image assessment approaches is recognized as a necessary requirement for the CBP to move from consideration to adoption of a satellite-based annual SAV cover assessment for tracking and reporting purposes in the program.

Refinement and improvement of the work demonstrated in the presentation continues to address the needs for SAV cover using cost-effective satellite-based resource assessment. For example, blue carbon in seagrass ecosystems could be estimated from high resolution commercial imagery.

The work illustrated here shows a partly automated process supported with AI characterization algorithms that offer opportunities for improvements to efficiencies for a monitoring program as satellite-based assessment methods are considered. Guidance to support further improvement and application with the approach includes:

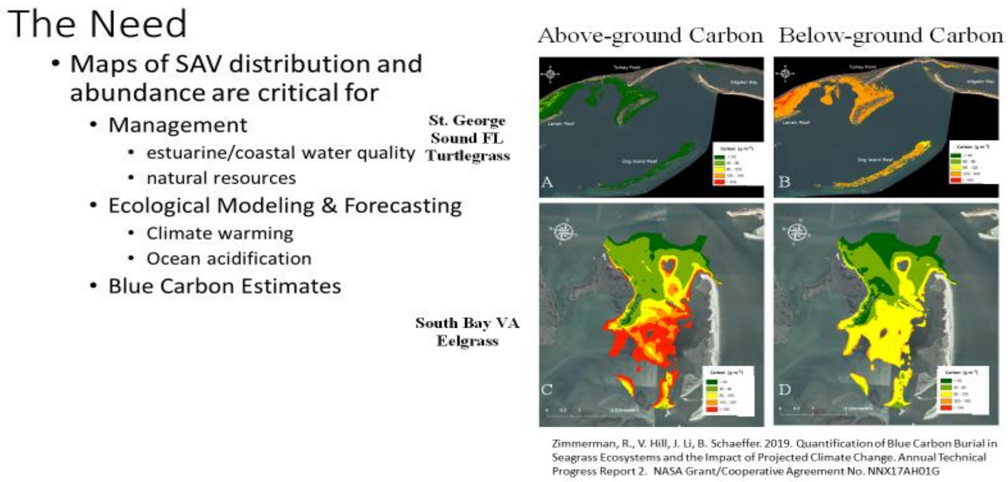
- Reprocess images when needed.
- Refining region-specific techniques.
- Documenting the “Frequency of detection” assessment approach using new satellite-based resources available from year-round, daily to sub daily imaging over the same

areas as a translation for density tracking cover status and change through time; the approach needs further calibration and verification.

- Use of the high frequency of satellite images to overcome turbidity and sparse SAV occupancy areas is a new option and opportunity previously unavailable with more standard models of satellite-sensor based deployments.
- Sparse areas are still identified with a protocol.
- Atmospheric correction with imagery needs to be addressed.

Automating the Quantification of Submerged Aquatic Vegetation from High Resolution Satellite Imagery — *Dick Zimmerman (ODU)*; Presentation Slides

New research on quantification of SAV from CSI illustrates the strength of advances informing detailed mapping of SAV cover in the Chesapeake Bay using satellite-acquired data and AI interpretation support. The ability to map SAV acres in Chesapeake Bay with fixed-wing aircraft-based hyperspectral imagery was highlighted, but expanding capacities to acquire, interpret and use satellite-based imagery were featured here.



The Need

- Maps of SAV distribution and abundance are critical for
  - Management
    - estuarine/coastal water quality
    - natural resources
  - Ecological Modeling & Forecasting
    - Climate warming
    - Ocean acidification
  - Blue Carbon Estimates

Zimmerman, R., V. Hill, J. Li, B. Schaeffer. 2019. Quantification of Blue Carbon Burial in Seagrass Ecosystems and the Impact of Projected Climate Change. Annual Technical Progress Report 2. NASA Grant/Cooperative Agreement No. NNX17AH01G

Figure 3. *Outline of community needs for SAV cover maps that recognize management, modeling, forecasting and blue carbon estimates. Images from Zimmerman et al. 2019.*

CBP community needs for such SAV cover mapping and assessment capacities include management, ecological modeling and forecasting, and blue carbon sequestration estimates (Figure 3). Varied challenges of maintaining the existing SAV aerial survey program for Chesapeake Bay have been highlighted in meetings and workshops in recent years; however, three primary issues have been identified:

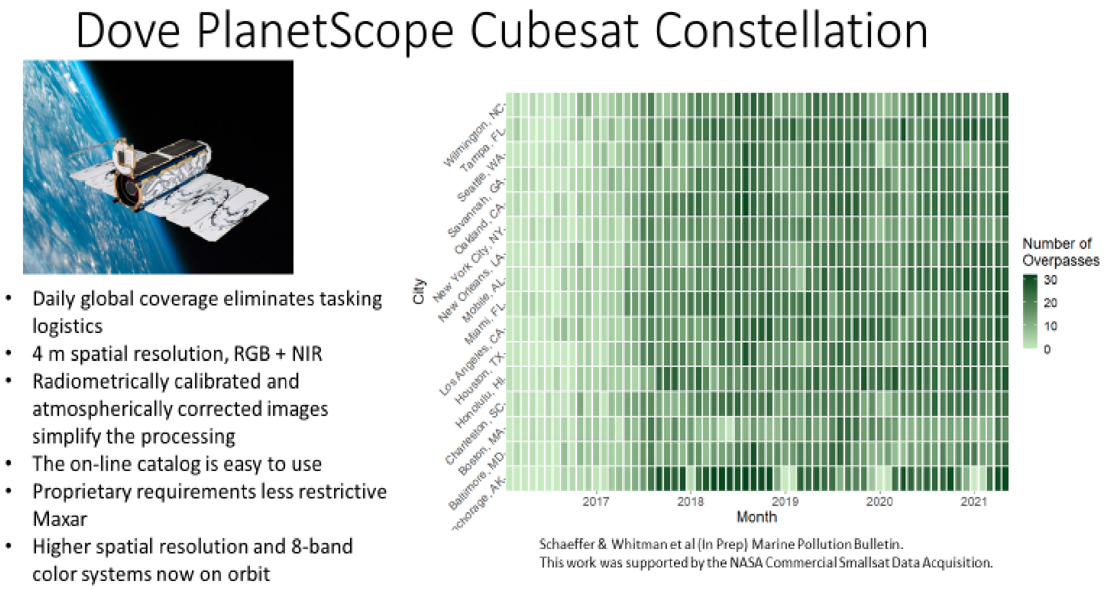
- aircraft costs and scheduling
- labor costs for manual photointerpretation, and
- increasingly limited access to restricted airspace.

To overcome these challenges, deeper exploration has been inspired by the research community on utility and applications of new satellite-based data resources.

There remains an outstanding question of whether satellite-based assessments and the interpretive algorithms used to characterize the sensor data could address those cost and resource challenges, improve efficiency of assessment, increase outputs, and further highlight that existing maps of relative abundance are not easily translated into absolute units of mass required for biogeochemical models or Blue Carbon estimates. Advantages and disadvantages of adopting a new satellite-based approach for CB SAV cover assessment were considered.

An important challenge to using the new high-temporal and spatial resolution satellite-based data streams discussed here includes how to integrate results of SAV cover maps derived from pixel-based classification algorithms with the time series of vector-based SAV cover maps historically derived as hand-drawn polygons. Pixel-based accounting of cover from satellite-based interpretation will return fewer hectares of SAV cover than polygon-based maps from the traditional SAV assessments by virtue of the present accounting rules for tallying SAV cover. The present hand-drawn SAV cover mapping creates bed boundaries containing variable bed densities, treating cover area independent of patch density equally in the tally. Pixel-based accounting is a direct accounting of presence-absence without a method yet for further defining bed boundaries that include unoccupied pixels as part of a bed. There is good agreement in area coverage between the two approaches of when SAV density is high. However, alignment of cover estimates between assessment methods focused on bed delineation including low SAV density areas (<50%) is needed.

Capabilities and availability of data from a candidate list of satellite resources were reviewed. Advantages and disadvantages of developing SAV assessments with each satellite considered resolution, frequency, availability across space and back through time, calibration and correction needs as well as accessibility. An example of such as assessment is shown for the PlanetScope SuperDove Constellation of cubesats (Figure 4).



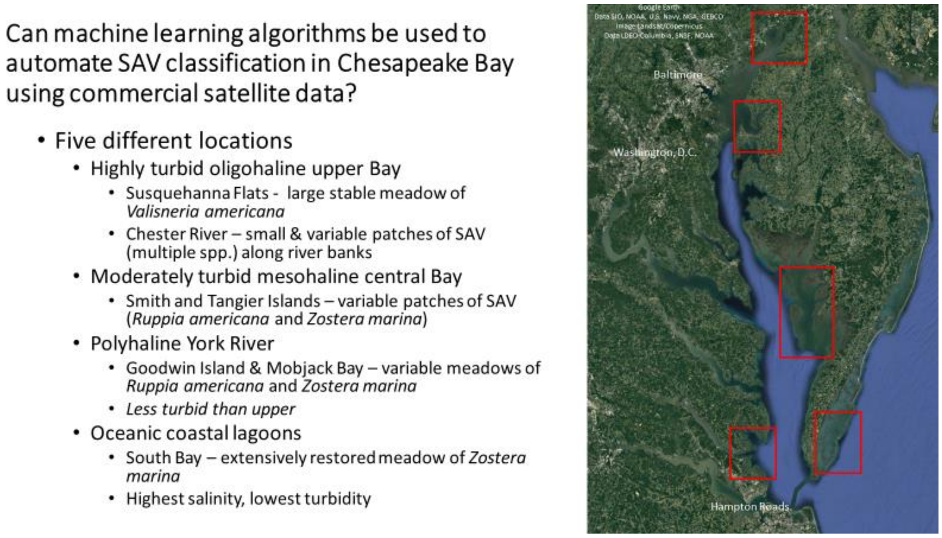
Dove PlanetScope Cubesat Constellation

- Daily global coverage eliminates tasking logistics
- 4 m spatial resolution, RGB + NIR
- Radiometrically calibrated and atmospherically corrected images simplify the processing
- The on-line catalog is easy to use
- Proprietary requirements less restrictive Maxar
- Higher spatial resolution and 8-band color systems now on orbit

Schaeffer & Whitman et al (In Prep) Marine Pollution Bulletin.
This work was supported by the NASA Commercial Smallsat Data Acquisition.

Figure 4. *Example satellite resource assessment provided by Dick Zimmerman, ODU. Assessment of SuperDove PlanetScope cubesat constellation of satellite resources to provide data at regular intervals, high resolution, calibration and corrections, access, and future outlook for SuperDove capacities to meet monitoring program needs. Image modifed from the final version in Schaeffer et al. 2022*

A key methodological need for working with CSI is high throughput CSI evaluation characterizing SAV cover in diverse habitat regions of Chesapeake Bay over many images at high resolution and with varied SAV species in each habitat. Highlights of a team studying 5 regions to test their AI driven approaches applied to select satellite-resources were provided (Figure 5).



Can machine learning algorithms be used to automate SAV classification in Chesapeake Bay using commercial satellite data?

- Five different locations
  - Highly turbid oligohaline upper Bay
    - Susquehanna Flats - large stable meadow of *Valisneria americana*
    - Chester River – small & variable patches of SAV (multiple spp.) along river banks
  - Moderately turbid mesohaline central Bay
    - Smith and Tangier Islands – variable patches of SAV (*Ruppia americana* and *Zostera marina*)
  - Polyhaline York River
    - Goodwin Island & Mobjack Bay – variable meadows of *Ruppia americana* and *Zostera marina*
    - *Less turbid than upper*
  - Oceanic coastal lagoons
    - South Bay – extensively restored meadow of *Zostera marina*
    - Highest salinity, lowest turbidity

Figure 5. *Study regions for machine learning algorithm testing by ODU to assess SAV cover in Chesapeake Bay and coastal bay habitats of the region using satellite-based image resources.*

Conclusions of the presentation highlighted extensive progress toward the development of a suitable monitoring protocol that could be adopted and operationalized for use in creating a satellite image-based Chesapeake Bay SAV cover survey. A summary of insights on the state of the science includes:

- Satellite image quality & quantity are improving for SAV mapping.
- Radiometrically calibrated and atmospherically products are readily available from several public & commercial sources.
- WorldView2/3 produce excellent high-resolution images; however,
  - tasking requirements presently makes their use for routine monitoring difficult,
  - radiometric calibration and atmospheric correction are not standardized across scenes, and
  - Maxar imposes considerable restrictions on public distribution of image data, while CBP requires accessibility to source data with its annual SAV survey.
- PlanetScope SuperDove cubesat constellation images
  - have been demonstrated to be suitable for automated AI/ML-based classification,
  - provide results from 4 m-scale satellite imagery that are consistent with hand-drawn polygons derived from VIMS 0.25 m aircraft imagery (see imagery at SAV Reports & Data | SAV Monitoring & Restoration | Virginia Institute of Marine Science),
  - provide similar Vector and Convolutional Neural Network algorithm-based results for SAV cover accounting from satellite images
  - require local training at this time, but training data can be provided from standardized locations

  - offer daily to sub-daily frequency of habitat images for Chesapeake Bay eliminating the tasking problems experienced attempting to work with the contracted satellite imagery provider
  - with a rate of at least 1 image per day acquisition, allows selection of the most usable images yielding 1-2 usable images per month, and
  - enables repeated classification of pixels that can produce unprecedented annual and seasonal time series.

Future directions of the work are aimed at overcoming challenges to the developing techniques for monitoring applications described as:

- Refining the machine learning algorithm
- Comparing performance of applying different approaches – e.g., Random Forest vs. CNN
- The need to eliminate training on each image
- Reducing SAV misclassifications using water quality flags for high turbidity and CDOM
- Apply repeated classification of multiple scenes to eliminate single-pixel errors
- Automating the workflow from image acquisition through pixel classification to generation of usable biogeochemical output products.

Satellite-Derived Seagrass Update — *Megan Coffer, David Graybill, Cindy Lebrasse, Wilson Salls, Peter Whitman, Blake Schaeffer, Victoria Hill, Richard Zimmerman*; Presentation Slides

Progress towards national applications of satellite imagery for coast-wide SAV assessment across a diversity of estuaries is now available. It is no longer a question of when we will be able to make SAV assessments from satellite-based data; increasingly, satellite-based SAV assessments are being completed (e.g., Lebrasse et al. 2022). Application of methods that can assess SAV cover in diverse habitats along the U.S. coast provided insights in this workshop into progress for applications of satellite-based SAV cover assessments in Chesapeake Bay.

Successes and challenges of seagrass monitoring with existing methods were highlighted while presenting the growing opportunities for quantifying seagrass with machine learning algorithms using satellite-based data. The new research featured here illustrates the use of a semi-automated method to quantify seagrass area, leaf area, and carbon using new quality control filters for CDOM, turbidity, and glint. Progress with applying the new methods provides an ability to differentiate spectrally similar seagrass and turbid water. When substrate is visible, seagrass can be mapped with strong agreement against field data, but when substrate is not visible, results can inform satellite targeting or field data prioritization. These advances have create the ability and capacity for larger scale quantification of seagrass status and change.

Among satellite data resources available, spectral bands that are commonly provided by remote sensing platforms (Green, Red, and NIR) are the most important for image classification of seagrass. Use of PlanetScope as a data source for SAV cover assessments is gaining increasing attention for several monitoring-based reasons. For example, as the PlanetScope constellation has grown, overpass frequency has increased to daily or near daily coverage over many areas. Further, by addressing the challenges posed by glint, past, present, and future sun glint conditions can be modeled and integrated into the workflow to ensure image quality for satellite platforms like PlanetScope that are recognized as sensitive to sun glint.

The future of seagrass assessment is moving towards semi-automated processing with machine learning and the use of high-temporal and high spatial resolution satellite data. Common interests for CBP SAV monitoring are being handled by the evolving techniques using satellite data for evaluating seagrass area. Further interests are aligned with CBP workgroups involving carbon assessments. Demonstrations applying these techniques to measure SAV cover have provided good results at multiple locations across the USA. Solutions for quality flagging are helping to increase the use of available imagery. Summary findings indicated that the use of image resources from new platforms offer the opportunity for substantial increases in spatial and temporal coverage to support SAV assessment protocol needs for CBP managers and researchers.

Report out on Results of STAC SAV/Satellite Workshop Tasking and Calibration Exercises: Implications and Feasibility of Moving to a Satellite-based SAV Monitoring Program — *David Wilcox and Chris Patrick (VIMS)*

"Tasking" a satellite for image collection is the process of a manager or researcher providing the agency, company, or institution in charge of data collection by a satellite imagery with an image request schedule (i.e., date, time, latitude and longitude). A satellite-tasking study was funded by EPA following recommendations provided during the successful 2020-2021 STAC-sponsored workshop *Exploring Satellite Image Integration for the Chesapeake Bay SAV Monitoring Program* (Landry et al. 2021). The steering committee of the Landry et al. workshop had recommended the following:

> "Following a full-bay tasking and calibration exercise, the FY19 workshop Steering Committee will reconvene to review the progress made and lessons learned during the tasking and calibration exercises. VIMS' report and an addendum with more detailed instructions and final recommendations will be submitted to STAC."

The subsequent study was performed using CSI collection. Results have been summarized from Wilcox and Patrick (2022) for informing the community on the state of the science for satellite-based SAV assessment when trying to mimic the data collection approach used to conduct the aerial SAV survey each year over Chesapeake Bay.

Background to the study indicated how single satellite images have been available from archives of image libraries. Such libraries contain images collected randomly over Chesapeake Bay across time for a variety of satellite missions. Images that coincidentally were collected at or near times and places where the present SAV aerial survey may have not been able to collect images during a year have been used (since 2018) to backfill SAV cover estimates in limited, local areas where aerial imagery could not be obtained due to most commonly weather, water quality, or national security air space restrictions. However, a complete bay-wide commercial grade satellite image library for a single season suitable for monitoring assessment purposes in Chesapeake Bay has never been assembled.

The VIMS goal was to task high resolution (approximately 1m^2) commercial satellite resources, applying guidance for defined by the National Geospatial Intelligence Agency (NGA), to acquire acceptable SAV imagery of the entirety of tidal waters of Chesapeake Bay in one SAV growing season (May-November). Permission was obtained from EPA CBP for VIMS to access the Maxar G-EGD online application and download Maxar data through USGS and the EROS Data Center using the Earth Explorer online tool (https://earthexplorer.usgs.gov). Detailed targeting of areas within the bay for image acquisition was coordinated with USGS staff and the USGS CIDR tool.

The objective of the work was aimed at duplicating the process used for acquiring aerial imagery each year by making requests for images across time and space, aligned with the timing for aerial image acquisition designed by VIMS targeting the best day or days of the year to capture maximum SAV biomass with minimal interference from tides. Acquired CSI would be compared for usability to aerial imagery for completing the annual SAV mapping survey in tidal waters of Chesapeake Bay. The effort tested steps needed in developing such monitoring capacity using satellite-based imagery.

Over the course of the study period, VIMS requested specific scenes on 110 dates that aligned with tide conditions and growing season. On four of these dates, the scene requested was successfully acquired, approximately a 4% success rate of acquired usable data to support annual SAV survey needs. It was unclear why so few of the specific requests were completed. Investigations are planned to attempt to understand the severe limitations encountered on the success rate of available satellite imagery.

VIMS additionally downloaded any available scenes captured by Maxar over Chesapeake Bay during the study period and acquired imagery for an additional 27 dates (76 scenes). VIMS staff performed a first pass usability assessment of low-resolution data from all 31 dates (84 scenes) using the Maxar viewer. Of these, 30 scenes were identified to cover non-tidal areas only, were obscured by clouds, or had extensive sun surface reflection and were rejected. The remaining 54 scenes cover 66% of Chesapeake Bay SAV potential habitat and were downloaded for further evaluation to assess what proportion were usable imagery. The scenes covered 23 dates, were large, covered a wide tidal range (high, mid, and low tides), and often contained at least some cloud cover.

Consistent differences were not found between SAV coverage mapped from aerial and satellite imagery, nor were there any clear patterns of bias in the results among the limited number of successful images acquired on dates, times, and in places coincident with survey needs. Except for the Widewater Quadrangle, where tidal differences appear to be the driving factor, the differences are 5% or less between image sources, and all VIMS mappers produced results both above and below the mean (Table 1). After completing this exercise, all three mappers reviewed the full set of imagery and evaluated the factors behind differences in the mapped beds.

Table 1. *VIMS comparisons between SAV mapped from aerial and satellite (Maxar) imagery during the pilot study.*

USGS Quadrangle	SAV Mapped from Aerial imagery (ha)	SAV mapped from Satellite imagery (ha)	Difference in SAV mapped (ha)	% Difference
Havre de Grace, MD	3,046.5	2,904.3	142.2	5%
Gunpowder Neck, MD	588.4	593.4	5.0	1%
Langford Creek, MD	93.6	95.8	2.2	2%
Widewater, VA-MD	568.0	498.5	69.6	12%
Franktown, VA	273.8	283.1	9.3	3%
New Point Comfort, VA	978.4	1,016.5	38.0	4%

In summary, some clear findings were identified:

- The study showed tasking requests with the currently contracted satellite imagery provider were successfully submitted; however, the effort was mostly unsuccessful in acquiring usable imagery in the requested areas for the date-time-locations requested.
- Requested areas were often acquired on dates other than the date requested. The resulting images were therefore collected during inopportune times, e.g., higher tides than the target of lowest tides to support effective evaluation of SAV cover.
- The tasking effort attempted to collect full bay coverage with satellite imagery; however, only a portion of the Bay (66%) was covered with any available satellite imagery that might be usable; true coverage was even lower due to images collected at times other than those requested coinciding with, for example, unsuitable tide or turbidity.
- Fixed-wing aircraft aerial image collection resulted in complete Bay coverage during the study. This method is flexible in the location and timing of image acquisition to adapt to local conditions in real time.
- Differences in tidal conditions and cloud cover seemed to have a stronger influence on the results than the type of imagery or which mapper completed the work.
- The lower resolution of imagery from the currently contracted provider compared to the aerial imagery resulted in smaller or sparser beds being hard to discern in some cases.

Suggestions for further work include:

- Continue to acquire satellite imagery but focus on areas where restricted access makes aerial acquisition difficult.

- Work with USGS, NGA, and satellite imagery providers to better understand the factors that control their image collection relative to the requested schedule for images. Determine if the targeting success rate can be increased while working with available satellite imagery.

Session 2. Advanced monitoring approaches to enhance tidal Chesapeake Bay habitat assessment Water clarity and Chlorophyll *a,* April 22, 2022.

Advanced Monitoring Focus: Overview on Water Clarity and Chlorophyll *a* Criteria Attainment Assessment in Chesapeake Bay

Water clarity introduction

The need for a simultaneous water clarity acres-assessment of all 92 Chesapeake Bay segments within a single year has been capacity limited. For water quality standards purposes, water clarity assessment in Chesapeake Bay tidal waters is evaluated by SAV acreages measured in each segment annually compared against goal acreages; the best year of a three-year assessment is used to evaluate attainment of the standard. However, "water clarity acres" can also be assessed. The water clarity equivalent acreage of the SAV acreage goal for a segment is derived using a 2.5x multiplier of the SAV goal acres of a segment. (USEPA 2007). This clarity-acres equivalence goal acknowledges that habitat can be of sufficient quality and not yet be colonized or in the process of SAV acreage expansion in response to the suitable conditions. Therefore, crediting restoration progress is accomplished when actual SAV acres in a segment may be below the goal but habitat conditions to accommodate SAV acres is achieved.

Specific to monitoring, however, the water clarity acres assessment, based on DATAFLOW surface mapping of water quality measures and translated into K_d using a regression developed from point measurements (USEPA 2008), is time and labor intensive. As a function of the monitoring and assessment methodology and existing capacity, the shallow water monitoring program started in 2003, and it has taken over 20 years to complete one circuit of the entire bay when applying water clarity acres methodologies. Ideally, a Bay-wide water clarity assessment would be completed in tandem with the SAV survey as an annual full survey of the 92 segments in the tidal waters. The National Oceanic and Atmospheric Administration (NOAA) National Centers for Coastal Ocean Science (NCCOS) and Turner et al. (2023) have demonstrated that satellite-based assessments of Bay-wide water clarity (expressed for a variety of clarity metrics) offer new opportunities to leverage research. Their research offers new opportunities to integrate new data streams and assessment protocols to derive annual Bay-wide water clarity assessment products that align with SAV survey results and support a more complete, timely, and efficient evaluation of our Bay clarity condition.

Workshop presentations during the segment on the State Water Clarity Assessment Review reviewed the spectrum of jurisdiction-specific assessment methods as a foundation for our understanding of present water clarity assessment capacity. The key here is that, unlike the SAV cover survey, water clarity (i.e., K_d) measured to create an assessment of water clarity acres for regulatory purposes is assessed on only a small subset of segments annually. Water clarity/SAV assessments are elements of water quality standards attainment assessments associated with Chesapeake Bay TMDL (USEPA 2010) interests and Clean Water Act 305b Integrated Report updates States provide EPA on the impairment status of waterways. For the tidal waters of Chesapeake Bay, the assessment structure is built around a 3-year assessment period. Assessment work occurs annually.

The workshop segment focused on resources and insights for extending present water clarity monitoring approaches to create bay-wide, annual, clarity-related assessments. The time was used to recognize advances in research and analysis that provide options and opportunities for annual bay-wide clarity conditions for improving upon the current, more limited scale for water clarity acres assessments. Presentations illustrate summaries of condition assessments and consider opportunities for expanding annual assessment support to the bay-wide scale through the use of advanced approaches that are focused on the use of remotely sensed data resources.

Chlorophyll a introduction

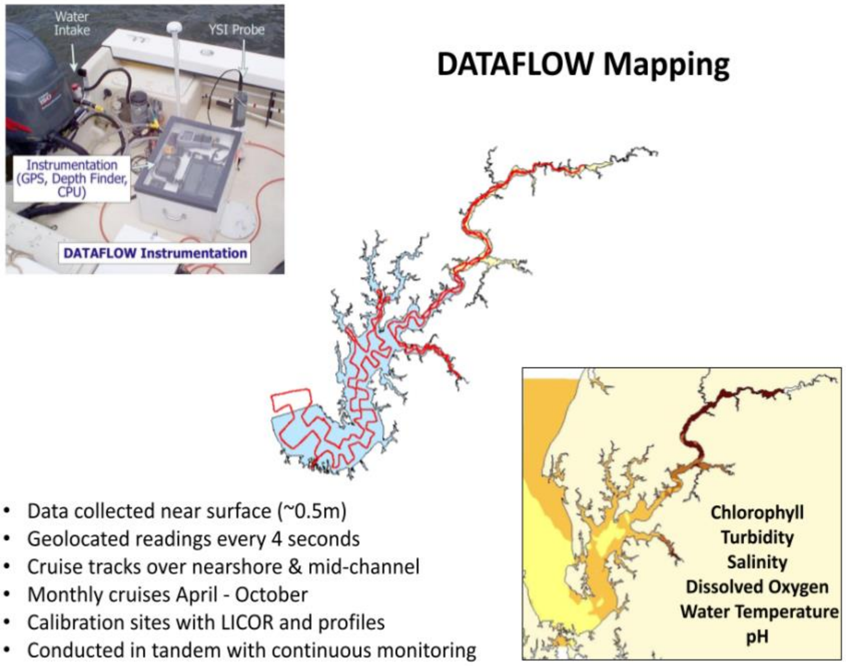
NOAA NCCOS produces satellite-derived products for chlorophyll *a*, conditions are mapped across all the tidal waters of Chesapeake Bay. New products are being developed to quantify some of the HABs in the bay. He et al. (2021) published an 11-year time series of Chesapeake Bay chlorophyll *a* patterns using publicly available satellite image resources demonstrating that within-year bay-wide condition and between year condition change assessment is conceivable if not already achievable. Chlorophyll *a* assessment approaches were reviewed, and insights into the state of new research with remote sensing-based data were presented.

The focus of this combined water clarity and chlorophyll *a* session was to evaluate the capacity of the research advances and applications that have developed for water clarity and chlorophyll *a* habitat assessment through satellite-based data and coincident published algorithms for image characterization to be operationalized for monitoring purposes. Coincidentally, community understanding was sought on limitations and considerations necessary to overcome barriers to implementing use of available data sets for annual habitat monitoring and water quality assessment purposes.

State Water Clarity Assessment Review

MD and VA Water Clarity Assessment — *Mark Trice (MD DNR), David Parrish (VIMS)*; Presentation Slides

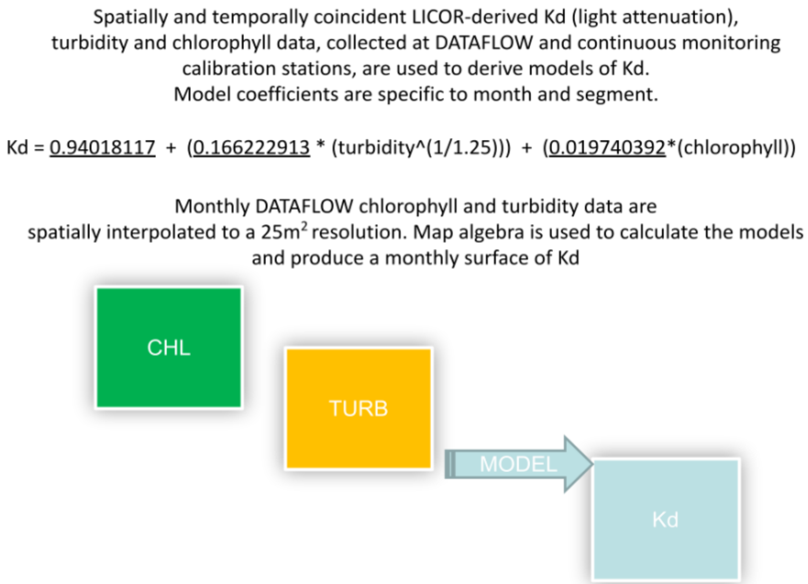
Each State's water clarity acres assessment process was presented and concluded with assessment challenges. For the process, under the existing regulatory assessment for water clarity in Chesapeake Bay, if a segment meets its SAV acreage goal during a 3-year assessment period, the Chesapeake Bay segment ***passes*** its segment specific water clarity criterion, meeting the definition of achieving the water quality standard for clarity in that segment. If a segment does not meet its SAV acreage goal in any of the three years, it ***fails***. If data do not exist, the segment ***fails***. However, if surface mapping (DATAFLOW) water quality data exist (Figure 6), a water clarity assessment is performed as an alternative approach to assessing SAV habitat quality towards meeting management efforts to achieve the water clarity goals (USEPA 2008).



- Data collected near surface (~0.5m)
- Geolocated readings every 4 seconds
- Cruise tracks over nearshore & mid-channel
- Monthly cruises April - October
- Calibration sites with LICOR and profiles
- Conducted in tandem with continuous monitoring

Figure 6. *DATAFLOW data collection method for water quality measures needed to produce a water clarity acres assessment in a Chesapeake Bay management segment.*

DATAFLOW data are used to create the segment level water clarity assessment (Figure 7). The key water quality parameters needed to develop the models are concurrent point measurements of K_d (the light attenuation parameter) and its predictors, chlorophyll and turbidity. Regressions were developed to be month and segment specific.



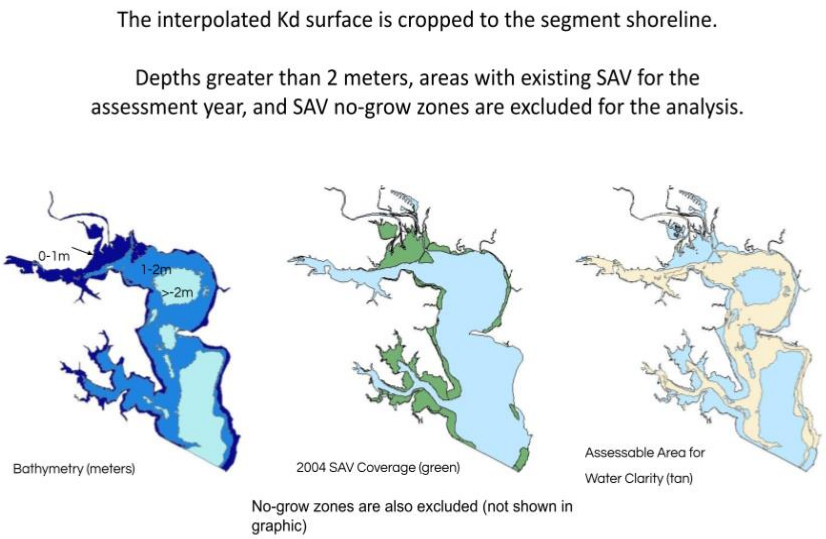
Spatially and temporally coincident LICOR-derived Kd (light attenuation), turbidity and chlorophyll data, collected at DATAFLOW and continuous monitoring calibration stations, are used to derive models of Kd. Model coefficients are specific to month and segment.

$$Kd = \underline{0.94018117} + (\underline{0.166222913} * (turbidity^{\wedge}(1/1.25))) + (\underline{0.019740392} * (chlorophyll))$$

Monthly DATAFLOW chlorophyll and turbidity data are spatially interpolated to a $25m^2$ resolution. Map algebra is used to calculate the models and produce a monthly surface of Kd

Figure 7. *Method detail on how DATAFLOW data are converted to Kd data to support Chesapeake Bay water clarity acres assessments.*

The resulting DATAFLOW chlorophyll and turbidity data are spatially interpolated in Geographic Information System (GIS) and then input into the model to derive a map of K_d at a 25-m^2 pixel resolution. The K_d layer is cropped to the bathymetry of the critical SAV habitat (depths of 2 meters or less) in the management segment (Figure 8). Some segments may have habitat features that result in areas designated as “no grow zones.” No grow zones are excluded from the available habitat area being assessed (e.g., dynamic nearshore habitat subject to erosion and wave action along the Calvert Cliffs region). Additionally, existing SAV acreage in a segment is excluded from the assessment area as having already passed criteria. K_d results are assessed against published criteria for water clarity depending on the grow zones (Table 2). Water clarity acres passing the K_d threshold are calculated for each monthly dataflow cruise during April–October, and averaged. The average is compared to the segment’s SAV goal multiplied by a water clarity acreage-to-SAV acreage translation factor of 2.5, minus the existing SAV acreage for the year being assessed. This factor has been determined previously such that for a particular area of SAV it requires 2.5x that area of suitable light conditions to support SAV survival, growth and reproduction to sustain the beds (USEPA 2007).


The interpolated Kd surface is cropped to the segment shoreline.

Depths greater than 2 meters, areas with existing SAV for the assessment year, and SAV no-grow zones are excluded for the analysis.

No-grow zones are also excluded (not shown in graphic)

Figure 8. *An example of a K_d mapped area and subsequent cropping to shallow water habitat area essential to the water clarity acres assessment needs in each Chesapeake Bay segment.*

Table 2. *Critical K_d values for threshold assessment of meeting goal light conditions for the habitat, published in USEPA (2003). K_d is the light attenuation measure, PLL is known as Percent Light at Leaf, and depending on where the segment is located in the tidal waters, the applicable grow zone may be out to 1 or 2 m. The PLL values differ according to plant requirements in different salinity zones.*

Kd Threshold

PLL	**Zones**	
	0-1m	**1-2m**
0.22	1.51	0.76
0.13	2.04	1.02

Continuing methodology challenges for assessing water clarity acres were outlined as guidance for consideration by the monitoring program going into the future toward improving assessment efforts:

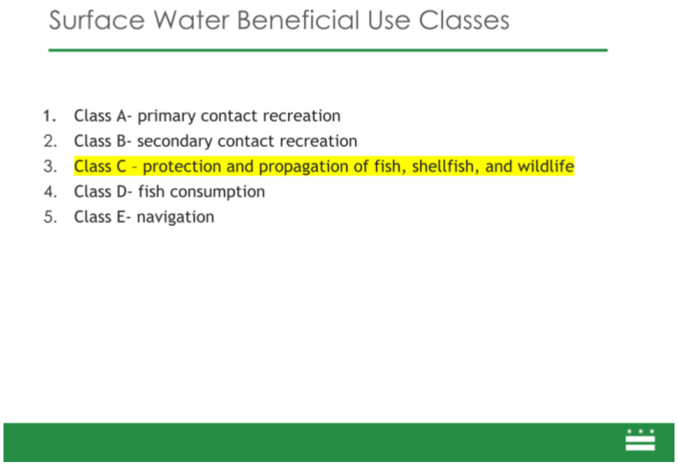
- Segments with low acreage goals like the Wicomico River can easily pass the water clarity acres goal by having one monitoring cruise with good clarity measures. The method might consider an update indicating minimum numbers of cruises needed to meet the criterion.
- Segments with high SAV cover but that do not meet their goal may not pass water clarity acres due to unmonitorable regions (upriver shallows of the Piscataway Creek).
- Segments with high SAV goals and moderate/high SAV may not pass water clarity acres due to insufficient remaining shallow water habitat associated with the 2.5 multiplication

factor (segments CHOMH2, LCHMH, CHSMH, EASMH, CHOMH1, HNGMH, POTOH in 2006-2008 assessments).

- Segmentation may unrealistically affect assessment, e.g., the Rhode River has a large bay front section of shoreline that passes clarity but may not be suitable for the SAV growth zone. No grow zone characterizations should be revisited.
- The amount of habitat that passes in the 1–2-meter zone is small across all segments currently.
- Temporal/spatial timings of clarity pass/fail are not considered.
- Calibration data may not capture the full range of data and therefore can produce models where no data could pass the criteria.

D.C. Water Clarity Assessment — *Nicoline Shulterbrandt (DOEE)*; Presentation Slides

Waters in Washington, D.C., have clarity standards. The jurisdiction has adopted the EPA 2003-2017 published guidance for ambient water quality protections in tidal waters of Chesapeake Bay and its subestuaries, but their waters are assessed as measures of Secchi and turbidity criteria at this time compared to the K_d measures used in MD and VA. Beneficial uses for which the clarity assessment applies fall under their Class C designated use (Figure 9).



Surface Water Beneficial Use Classes

1. Class A- primary contact recreation
2. Class B- secondary contact recreation
3. Class C - protection and propagation of fish, shellfish, and wildlife
4. Class D- fish consumption
5. Class E- navigation

Figure 9. *Washington, D.C. surface water beneficial use classes. Class C is where water clarity assessment is applied.*

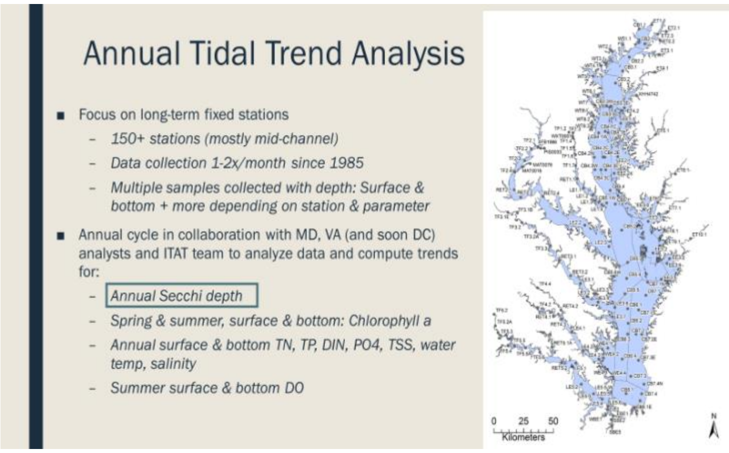
Class C waters for the District of Columbia water quality standards were described as including narrative criteria, bioassessment, physical habitat assessment, and numeric criteria including those for turbidity and Secchi depth. for the protection of aquatic life. Operationally, attainment of the Class C use is evaluated using bioassessment, physical habitat assessment, and numeric criteria.

Discrete data are collected and evaluated. The criterion threshold for Secchi depth is a seasonal assessment average (April–October) over a 5-year assessment period is 0.8 m. The turbidity criterion is 20 NTUs, where <10% of samples can be above the threshold for the assessment period. Results from 2020 and 2022 assessments showed Potomac River, Anacostia River, and Rock Creek tributaries exceeded their turbidity criteria and failed to attain the standards.

Resources and Insights for Extending Present Water Clarity Monitoring Approaches to Create Bay-wide Annual Clarity-related Assessments

Short and long-term station-specific water clarity Secchi trends — *Rebecca Murphy (UMCES)*; Presentation Slides

The Chesapeake Bay long-term tidal water quality monitoring program has conducted annual assessments since 1985 (Figure 10). Annual trend assessments are conducted in collaboration with the bay jurisdictions and the CBP Integrated Trends Analysis Assessment Team. Long-term trends refer to trends starting in 1985 up to the most recent available year of data. For this presentation, the most recent data are for 2020. Short-term trends represent trends over the most recent decade for signals of recent response to management actions. Here we focus on Secchi depth.

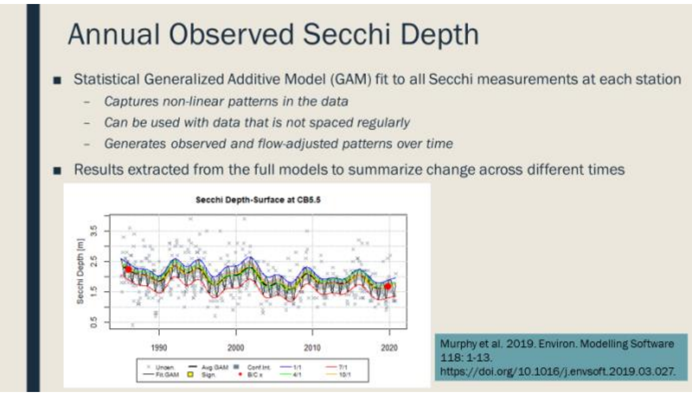


Annual Tidal Trend Analysis

- Focus on long-term fixed stations
    - *150+ stations (mostly mid-channel)*
    - *Data collection 1-2x/month since 1985*
    - *Multiple samples collected with depth: Surface & bottom + more depending on station & parameter*
- Annual cycle in collaboration with MD, VA (and soon DC) analysts and ITAT team to analyze data and compute trends for:
    - *Annual Secchi depth*
    - *Spring & summer, surface & bottom: Chlorophyll a*
    - *Annual surface & bottom TN, TP, DIN, PO4, TSS, water temp, salinity*
    - *Summer surface & bottom DO*

Figure 10. *Outline of the Chesapeake Bay tidal water quality monitoring program sampling frame and analysis targets for trend analysis.*

Bay trends are presently assessed using Generalized Additive Models (GAMs) following the methods summarized in Murphy et al. 2019, example shown in the presentation is shared here in Figure 11. Secchi trends were run on unadjusted observed results as well as flow-adjusted results; flow adjusted results are results that are standardized as if flow had been at average flow each year of the period throughout the period of assessment.



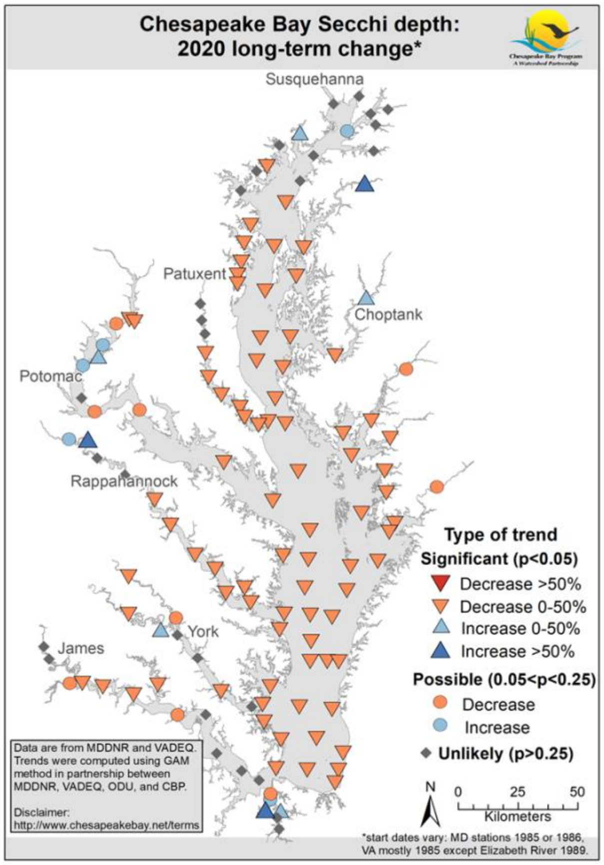
Annual Observed Secchi Depth

- Statistical Generalized Additive Model (GAM) fit to all Secchi measurements at each station
  - *Captures non-linear patterns in the data*
  - *Can be used with data that is not spaced regularly*
  - *Generates observed and flow-adjusted patterns over time*
- Results extracted from the full models to summarize change across different times

Murphy et al. 2019. Environ. Modelling Software 118: 1-13. https://doi.org/10.1016/j.envsoft.2019.03.027.

Figure 11. *Description of the Generalized Additive Model assessment for trends.*

Results of recent analyses showed long-term trends are dominated by degrading Secchi trends throughout the tidal waters of Chesapeake Bay (Figure 12). The same basic pattern of degradation is found in flow-adjusted assessment. Short-term trends show some recent northern bay improvements in Secchi measures; however, most areas are showing no trend, representing plateaus in the trajectories observed at many stations in the long-term analysis results (Figure 13).



Chesapeake Bay Secchi depth:
2020 long-term change*

Data are from MDDNR and VADEQ. Trends were computed using GAM method in partnership between MDDNR, VADEQ, ODU, and CBP.

Disclaimer: http://www.chesapeakebay.net/terms

*start dates vary: MD stations 1985 or 1986, VA mostly 1985 except Elizabeth River 1989.

Figure 12. *Chesapeake Bay long-term (1985-2020) trends in Secchi depth.*

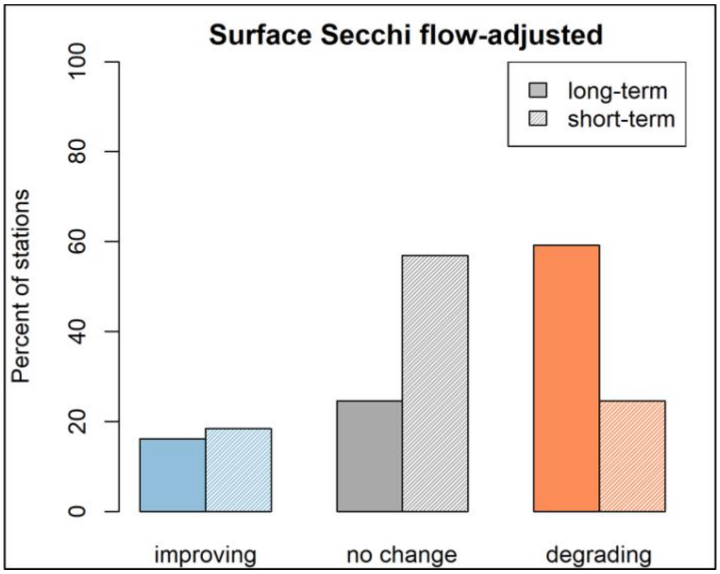


Figure 13. *Bar chart comparing long-term (1985-2020, left bar in each category) and short-term (2011-2020, right bar in each category) trend summaries for Secchi depth in tidal waters of Chesapeake Bay. Trend distribution shifts are seen where long-term trends are dominated by 'degrading' Secchi depths while short-term trends are dominated by 'no change.'*

For reference, the complete trend assessment results are available online:

CBP Integrated Trends and Analysis Team (ITAT) webpage

- *2020 maps are available for all parameters.* *https://www.chesapeakebay.net/who/group/integrated_trends_analysis_team*

Baytrendsmap webpage

- *Summary file, table, and interactive website to explore the trends.*

https://baytrends.chesapeakebay.net/baytrendsmap/

Remote sensing of Water Clarity in the Chesapeake Bay: Advantages and disadvantages — *Jessie Turner (U Conn and VIMS)*; Presentation Slides

Water clarity can mean something different to each person. Metrics of interest can vary depending on the research or management interest. For example, Secchi depth, attenuation, and turbidity are often used to interpret clarity; component metrics of colored dissolved organic matter, chlorophyll and total suspended solids that influence observations and the interpretation of clarity (Figure 14) are also used. These metrics are often assessed conditions measured at a point location at one moment in time. More recently, these metrics may be observed or interpreted using fixed-depth, sensor-based data time series or a transect sensor data collection approach with results interpolated into map coverage of conditions for an area. Satellite-based remote sensing resources have added regional synoptic coverage and large-scale condition mapping opportunities for monitoring and assessment.

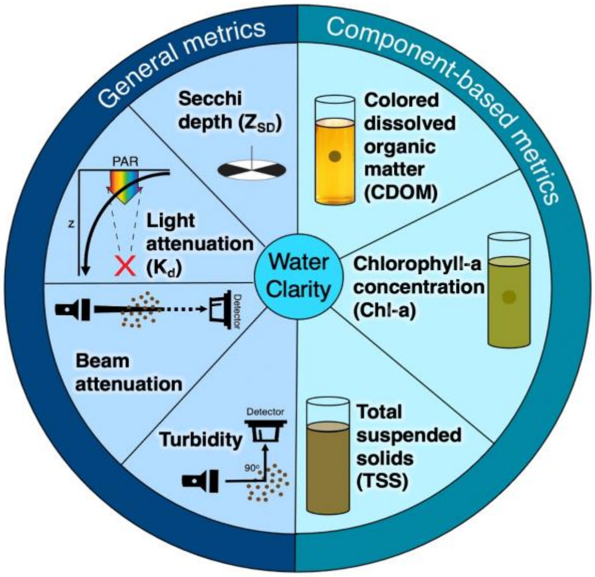


Figure 14. *General and component-based metrics of water clarity (Source: Turner et al. 2023).*

Two ends of the spectrum of opinion on satellite-data use for water clarity assessments were highlighted. On one end, satellite-based data are now freely available and provide great areal coverage and long time series. On the other end of the spectrum, there is a perspective that the Bay is too optically complex to reliably estimate water clarity for the region. The view provided in the presentation split the difference between these two ends of the spectrum. There are use benefits with satellite-based resources acknowledging the advantages and disadvantages of assessing clarity with remote sensing methods.

Remote sensing reflectance showed reflectance wavelength signature patterns are associated with different water clarity component-based metrics. Spatial resolution per pixel, sensor bands represented, and overpass frequency are elements considered when using satellite-based data sources to asses water clarity because each of those elements may influence monitoring protocol development for future satellite-based water clarity assessment protocols. Using time series of imagery and leveraging understanding about sensor band relationships representing component clarity metrics of interest, long-term trends were assessed and indicate improvements in water clarity with reductions in TSS and a greater representation of plankton in the reflectance signatures for the Chesapeake Bay mainstem (lower bay) in particular.

A Florida Virtual Buoy System was reviewed as an example of a satellite-based water quality monitoring system for creating long-term time series assessments to evaluate change over time (Hu et al. 2014). The method was effective for evaluating change in Florida waters, but the same methods may not be directly adoptable for application in the optically complex waters of the Chesapeake Bay system.

Future satellite missions will likely diversify the opportunities for image use in water clarity assessments. Tradeoffs on selecting a satellite-resource for a monitoring program will remain. The suggestions for monitoring program development with remote sensing resources follows the fundamental rule of choosing a data resource that 1) considers the tradeoffs involving the data source (Table 3), 2) represents the best measurement for the specific research or management needs/goals, and 3) validates the measurement that is most needed.

Table 3. *Advantages and disadvantages of satellite-based data for water clarity assessment.*

Advantages	Disadvantages
• Synoptic coverage • Already in orbit, low cost, freely available • High temporal, spatial resolution • Estimates possible	• Clarity in the Bay is complicated in situ, things like K_d, Secchi are decoupled • Optically complex, Chl-a looks like CDOM • Lower accuracy

Merging Landsat-8, Sentinel-2, and in situ data to improve coastal water clarity monitoring

— *Sarah Lang (University of Rhode Island)*; Presentation Slides

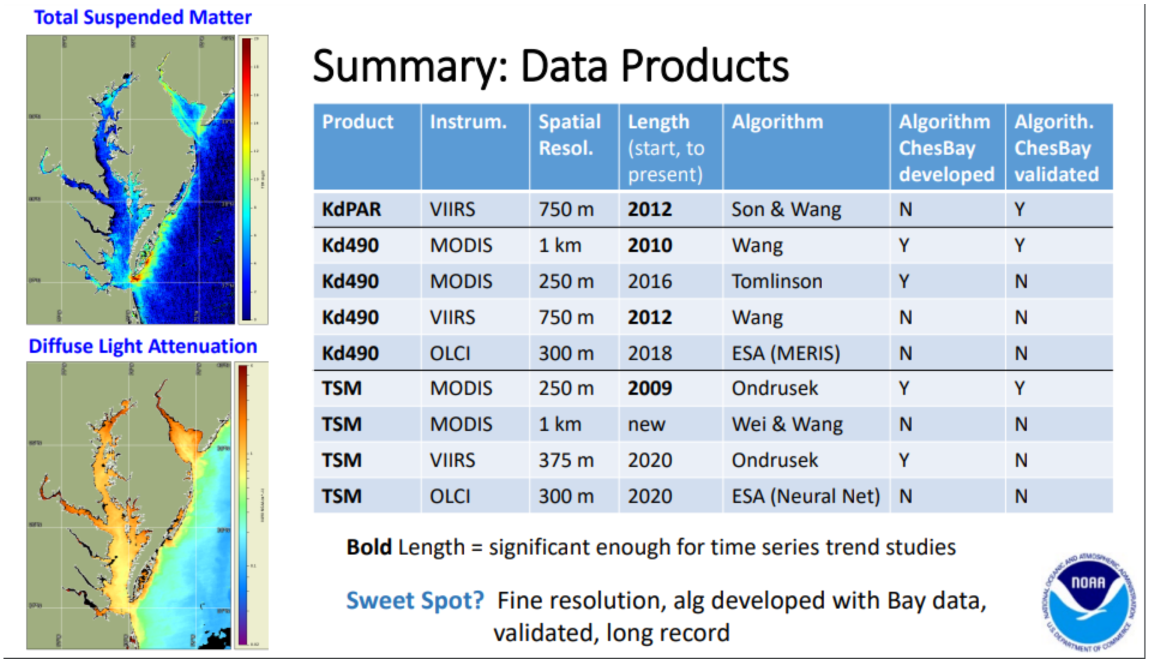
A challenge of discrete sampling programs is the ability to capture temporal and spatial variability in water clarity across measurement scales available to best characterize conditions. Ocean color algorithms applied to satellite sensor results offer a means of characterizing water clarity over regional scales. Regional scales of assessment remain a strong interest for increasing the Chesapeake Bay water quality monitoring program capacity to assess water clarity acres across the estuary.

In situ water quality data are essential for evaluating the performance of ocean color algorithms to calibrate and validate satellite-based evaluations against discrete field measures. Existing algorithms applied to Landsat 8 and Sentinel-2 imagery were shown to overestimate Secchi depths. However, algorithm performance is being improved over the performance of the original, published algorithms used for Secchi depth estimation here. Regional assessment with local scale variability captured by working with the satellite imagery on the coastal bays test area has been demonstrated.

Suggestions for CBP monitoring protocol development using satellite imagery were to 1) create a satellite product harmonious with a long term in situ dataset, 2) apply the updated algorithm approach shown in the presentation using a ±1 day window of matching in-situ with satellite-based measures and expand the window as is suitable for the work, 3) address atmospheric correction – Case-2 Regional CoastColour (C2RCC) (Windle et al., 2022), and 4) consider the use of drones to support clarity monitoring.

NOAA satellite-based Products for Chesapeake Bay Water Clarity — *Ron Vogel (NOAA Satellite Applications & Research / CoastWatch)*; Presentation Slides

NOAA has a strong history of developing data products from satellite image assessments. Resolution in space and time have long been important considerations for CBP uses of satellite imagery for water quality assessment. Government satellites (VIIRS and MODIS) have K_d and total suspended matter (TSM) products developed on algorithms validated on Chesapeake Bay (Figure 15). Product resolution is 250 m to 1 km in space. Duration of satellite operation offers some support for time series trend analysis (e.g., VIIRS K_d PAR, Figure 15). Data considerations for the application of these products include - Broad geographic coverage for overview of spatial patterns, daily overpasses from 5 satellites (instruments: MODIS (1), VIIRS (2), Ocean and Land Colour Instrument (OLCI) (2)), overpass times: (OLCI: ~10:30 AM local time • MODIS & VIIRS: ~3:00 PM local time), and course to fine spatial resolutions: 1 km to 250 m, and surface measurement only (euphotic zone).



Summary: Data Products

Product	Instrum.	Spatial Resol.	Length (start, to present)	Algorithm	Algorithm ChesBay developed	Algorith. ChesBay validated
KdPAR	VIIRS	750 m	**2012**	Son & Wang	N	Y
Kd490	MODIS	1 km	**2010**	Wang	Y	Y
Kd490	MODIS	250 m	2016	Tomlinson	Y	N
Kd490	VIIRS	750 m	**2012**	Wang	N	N
Kd490	OLCI	300 m	2018	ESA (MERIS)	N	N
TSM	MODIS	250 m	**2009**	Ondrusek	Y	Y
TSM	MODIS	1 km	new	Wei & Wang	N	N
TSM	VIIRS	375 m	2020	Ondrusek	Y	N
TSM	OLCI	300 m	2020	ESA (Neural Net)	N	N

Bold Length = significant enough for time series trend studies

Sweet Spot? Fine resolution, alg developed with Bay data, validated, long record

Figure 15. *Summary water clarity data products generated by NOAA.*

Clouds cause gaps in data collection; however, mitigations are possible using data windows and time averaging for example. Some algorithms have been developed with Bay in-situ data; validation accuracies are published for some products. Length of record is important to the CBP and may create one of the bigger challenges to adoption with CBP interests in data back to 1985 while satellite time series tend to be more recent, e.g., MODIS since 2009, VIIRS since 2012, OLCI since 2018. Mission-length reprocessing needed for full records.

Possibilities identified to push the state of the art improving product accuracy, coverage, or both include:

- Conduct cross-product validation study (e.g., refer to chlorophyll *a* comparison presentation from Tomlinson).
- Reprocess current satellite product(s) for entire mission length for augmenting CBP trend analyses.

- Develop multi-satellite continuity products, especially for bridging between satellite missions.
- Dedicated *in-situ* monitoring for satellite algorithm development, e.g., to match satellite overpasses
- Investigate higher resolution satellite options – 10's of meters or less but with trade-off of lower temporal frequency (e.g., Landsat 8/9 (USGS) or Sentinel-2a/2b (ESA/EUMETSAT) (Commercial).
- Research to improve atmospheric corrections, specifically for Chesapeake Bay.
- Research to improve algorithms.
- OLCI, with additional bands, shows promise but current algorithms neither developed nor validated for Chesapeake Bay.
- Intelligent algorithms.
- Policy development for NOAA-NASA-Academic engagement.

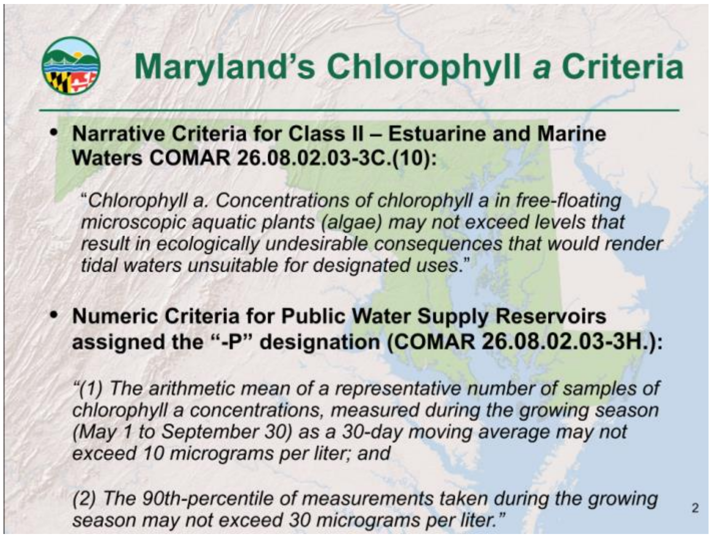
Chlorophyll *a*

State Chlorophyll Assessment Review

Presentation Summaries on Session, Chlorophyll a

MD Chlorophyll *a* Assessment — Slides prepared by *Matt Stover (MDE)*; Presentation Slides

Maryland follows narrative criteria directing chlorophyll *a* management in its regulations for its estuarine and marine waters, and quantitative criteria in its public water supply reservoirs (Figure 16). The narrative estuarine criteria were published in USEPA (2003) and subsequently adopted by the State for regulatory assessment and protection purposes. Tidal water quality monitoring thus far involves temporally intensive and spatially intensive data collections (Figure 17) with the capacity to leverage other data such as the Chesapeake Bay long-term water quality monitoring program low temporal density chlorophyll *a* data. Maryland representatives suggested continued CBP Criteria Assessment Protocol Workgroup meetings to be used to evolve tidal water quality criteria assessment protocols.



Maryland's Chlorophyll *a* Criteria

- **Narrative Criteria for Class II – Estuarine and Marine Waters COMAR 26.08.02.03-3C.(10):**

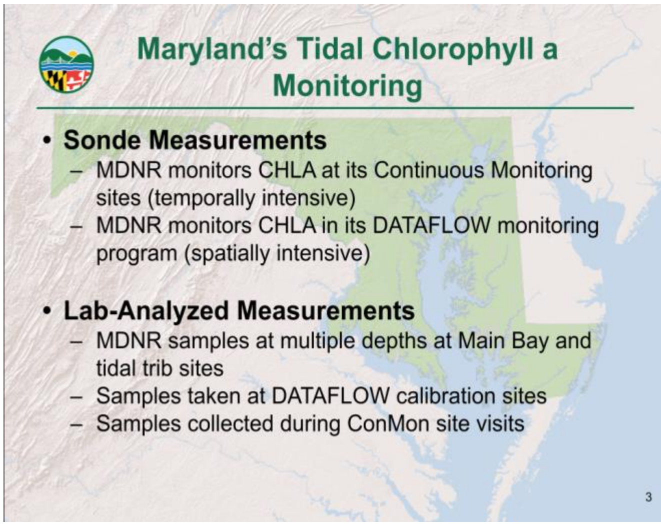
  "Chlorophyll a. Concentrations of chlorophyll a in free-floating microscopic aquatic plants (algae) may not exceed levels that result in ecologically undesirable consequences that would render tidal waters unsuitable for designated uses."

- **Numeric Criteria for Public Water Supply Reservoirs assigned the "-P" designation (COMAR 26.08.02.03-3H.):**

  "(1) The arithmetic mean of a representative number of samples of chlorophyll a concentrations, measured during the growing season (May 1 to September 30) as a 30-day moving average may not exceed 10 micrograms per liter; and

  (2) The 90th-percentile of measurements taken during the growing season may not exceed 30 micrograms per liter."

Figure 16. *Maryland's Chlorophyll a criteria.*



Maryland's Tidal Chlorophyll *a* Monitoring

- **Sonde Measurements**
  - MDNR monitors CHLA at its Continuous Monitoring sites (temporally intensive)
  - MDNR monitors CHLA in its DATAFLOW monitoring program (spatially intensive)
- **Lab-Analyzed Measurements**
  - MDNR samples at multiple depths at Main Bay and tidal trib sites
  - Samples taken at DATAFLOW calibration sites
  - Samples collected during ConMon site visits

Figure 17. *Maryland's outline of tidal chlorophyll monitoring.*

VA Chlorophyll *a* Assessment – *Tish Robertson*; Presentation Slides

Narrative criteria published in USEPA (2003) apply for all tidal waters in Virginia; however, the James River has had season-specific quantitative criteria supporting its water quality standards attainment assessments. In 2019, Virginia adopted updated chlorophyll *a* criteria for the tidal James River (VADEQ 2019). These criteria are based upon the findings of a multi-year evaluation (VADEQ 2016, 2019b) of the:

- Phytoplankton composition in the James River, especially of harmful algal blooms (HAB)-forming taxa.
- Toxicity of HAB-forming taxa in the James River.
- Water quality parameters correlated with phytoplankton biomass (DO, pH, and clarity).
- Ambient chlorophyll *a* concentrations in the James River.

In this overview, present criteria are shown to be assessed for 1-day median (mesohaline and polyhaline habitats), 1-month median criteria (tidal fresh segments) and seasonal means in all James River management segments (Figure 18).

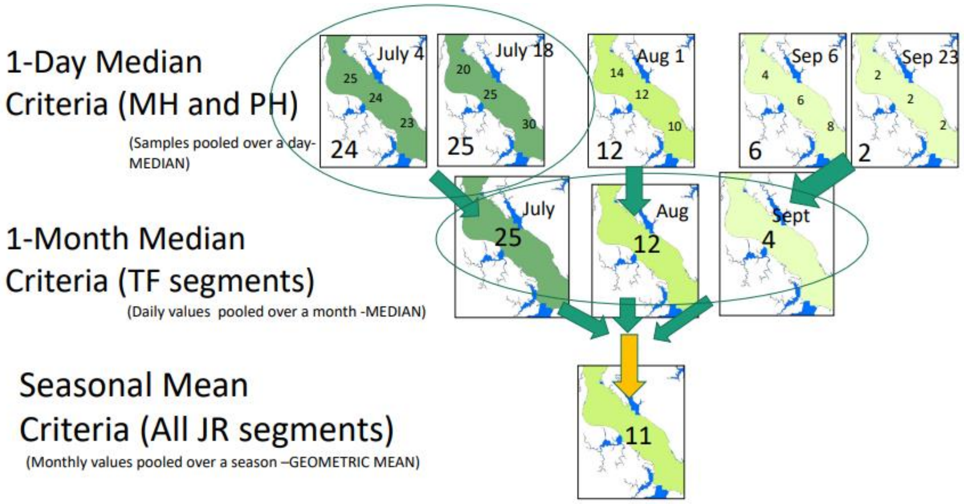


Figure 18. *VADEQ chlorophyll criteria assessments for the James River.*

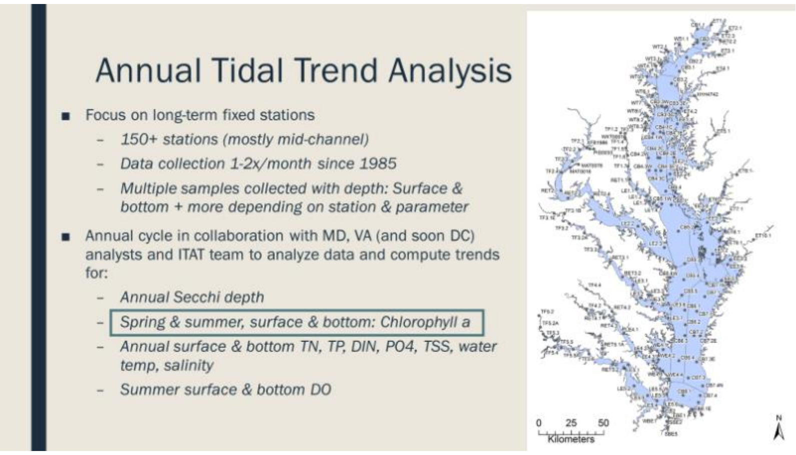
District of Columbia Chlorophyll *a* Assessment

For this workshop, the only information provided was that for Washington, D.C., a summer season mean criterion is assessed and reported against a 25 µg/L threshold.

Resources and Insights for Extending Present Chlorophyll *a* Monitoring Approaches to Create Bay-wide Annual Chlorophyll -related Assessments

Short and long-term station-specific chlorophyll *a* **trends** — *Rebecca Murphy (UMCES)*; Presentation Slides

The Chesapeake Bay long-term tidal water quality monitoring program has conducted annual assessments since 1985 (Figure 19). Annual trend assessments are conducted in collaboration with the bay jurisdictions and the CBP Integrated Trends Analysis Team. Long-term trends refer to trends starting in 1985 up to the most recently available year of data. For this presentation, the most recent chlorophyll *a* data are for 2020. Short-term (i.e., most recent 10-year) trends look at trends over the most recent decade for signals of recent response to management actions.

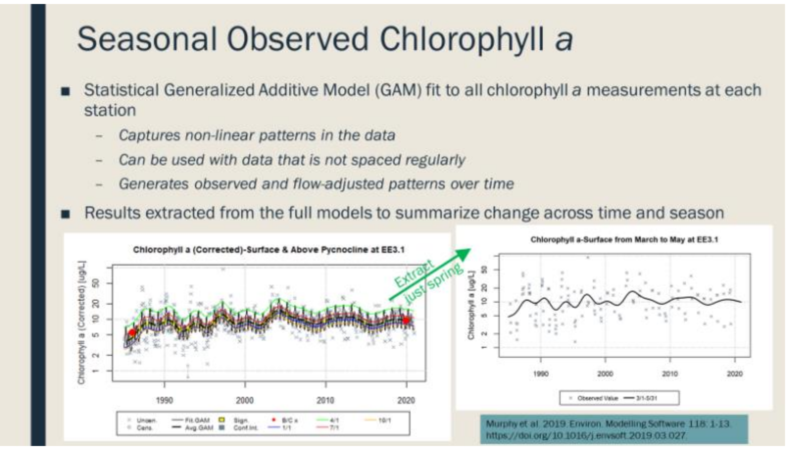


Annual Tidal Trend Analysis

- Focus on long-term fixed stations
  - *150+ stations (mostly mid-channel)*
  - *Data collection 1-2x/month since 1985*
  - *Multiple samples collected with depth: Surface & bottom + more depending on station & parameter*
- Annual cycle in collaboration with MD, VA (and soon DC) analysts and ITAT team to analyze data and compute trends for:
  - *Annual Secchi depth*
  - *Spring & summer, surface & bottom: Chlorophyll a*
  - *Annual surface & bottom TN, TP, DIN, PO4, TSS, water temp, salinity*
  - *Summer surface & bottom DO*

Figure 19. *Outline of the Chesapeake Bay tidal water quality monitoring program sampling frame and analysis targets for trend analysis.*

Bay trends are presently assessed using Generalized Additive Models (GAMs) following the methods summarized in Murphy et al. 2019 (Figure 20). Seasonal (spring and summer) chlorophyll *a* trends were produced for surface and bottom measures on unadjusted observed results as well as flow-adjusted results; flow-adjusted results are results that are standardized such that each year is treated as if flow had been average throughout assessment period.



Seasonal Observed Chlorophyll *a*

- Statistical Generalized Additive Model (GAM) fit to all chlorophyll *a* measurements at each station
  - *Captures non-linear patterns in the data*
  - *Can be used with data that is not spaced regularly*
  - *Generates observed and flow-adjusted patterns over time*
- Results extracted from the full models to summarize change across time and season

Murphy et al. 2019. Environ. Modelling Software 118: 1-13. https://doi.org/10.1016/j.envsoft.2019.03.027.

Figure 20. *Description of Generalized Additive Models (GAMs) applied to chlorophyll a trend assessments for Chesapeake Bay data, 1985-2020 (long-term) and 2011-2020 (short-term) seasonal (spring and summer) assessments of surface and bottom water chlorophyll a measures.*

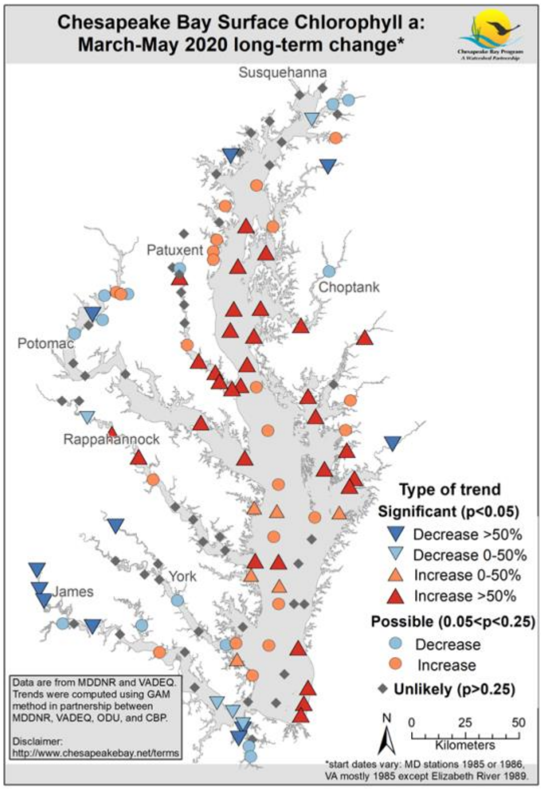
During the spring season in surface measures, the mainstem bay is dominated by long-term degrading trends (Figure 21). Improving and no-trend conditions are frequently observed in the tidal tributaries. Spring and summer results between long-term and short-term trends in surface water chlorophyll *a* show similar patterns with more degrading trends for long-term assessments but a shift toward no-trend and improving trends during the short-term 2011-2020 assessment (Figure 22). For the complete trend assessment results across the applicable seasons and depths, visit the following resources:

ITAT webpage

- *2020 maps are available for all parameters.* [*https://www.chesapeakebay.net/who/group/integrated_trends_analysis_team*](https://www.chesapeakebay.net/who/group/integrated_trends_analysis_team)

Baytrendsmap

- *Summary file, table, and interactive website to explore the trends.* https://baytrends.chesapeakebay.net/baytrendsmap/

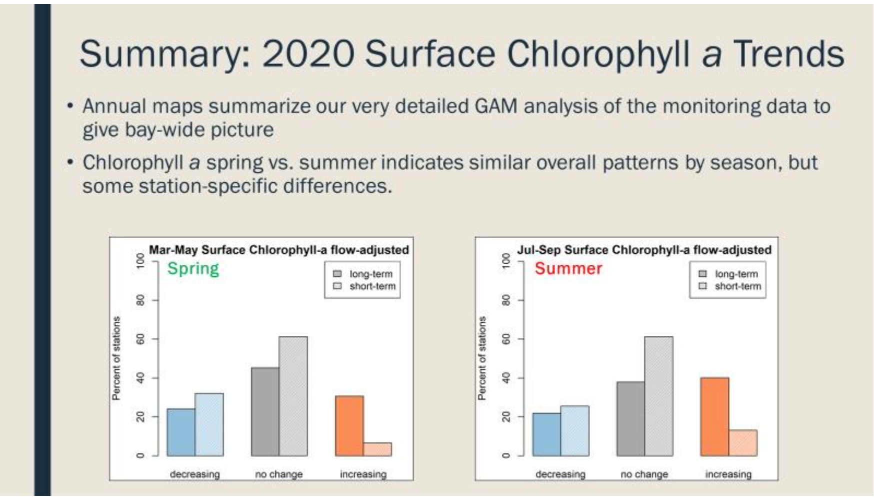


Data are from MDDNR and VADEQ. Trends were computed using GAM method in partnership between MDDNR, VADEQ, ODU, and CBP.

Disclaimer: http://www.chesapeakebay.net/terms

*start dates vary: MD stations 1985 or 1986, VA mostly 1985 except Elizabeth River 1989.

Figure 21. *Chesapeake Bay surface chlorophyll a, spring season (March-May), 1985-2020.*



Summary: 2020 Surface Chlorophyll *a* Trends

- Annual maps summarize our very detailed GAM analysis of the monitoring data to give bay-wide picture
- Chlorophyll *a* spring vs. summer indicates similar overall patterns by season, but some station-specific differences.

Figure 22. *Chart comparing long-term (1985-2020, left bar in each category) and short-term (2011-2020, right bar in each category) trend summaries for spring and summer flow-adjusted surface chlorophyll a measures in tidal waters of the Chesapeake Bay. Trend distribution shifts are seen where long-term trends are dominated by 'degrading' measures while short-term trends are dominated by 'no change.'*

USGS satellite-based Chlorophyll *a* assessment for Chesapeake Bay — *Kendull Wnuk (USGS)*; Presentation Slides

Diverse satellite resources now offer increased options to support satellite-based long-term water quality monitoring at the bay-wide scale throughout the year. Landsat satellite data were focused on here as an important resource given the variety of advantages recognized for using this resource contrasted against a set of disadvantages challenging its utility (Table 4). Training data for machine learning algorithm applications are highlighted (Table 5).

Table 4. *Pros and cons for using Landsat satellite-image time series in chlorophyll assessment in Chesapeake Bay.*

Advantages	Disadvantages
* Historical observations • Acquisitions from 1984 to present – aligns with history of Chesapeake Bay Program • Potential to fill gaps in historical Harmful Algal Bloom (HAB) record • Available *in-situ* data across time • Used to train machine language (ML) models • Relatively high spatial resolution • Spatially acute time-series analyses	• Relatively poor spectral resolution • Outclassed by Sentinel-2 & OLCI • Less accurate models

Table 5. *Training data for machine learning algorithm applications.*

Data matching application	Matching data for training
Red: Chlorophyll fluorescence survey data acquired from Chesapeake Bay Program – bay-wide fluorescence database	● 1984-2012 ● ~100,000 "matchups" (coincident, unobstructed Landsat acquisition)
Blue: Water quality portal and LAGOS-NE	● 1984-2018 ● ~5,000 matchups

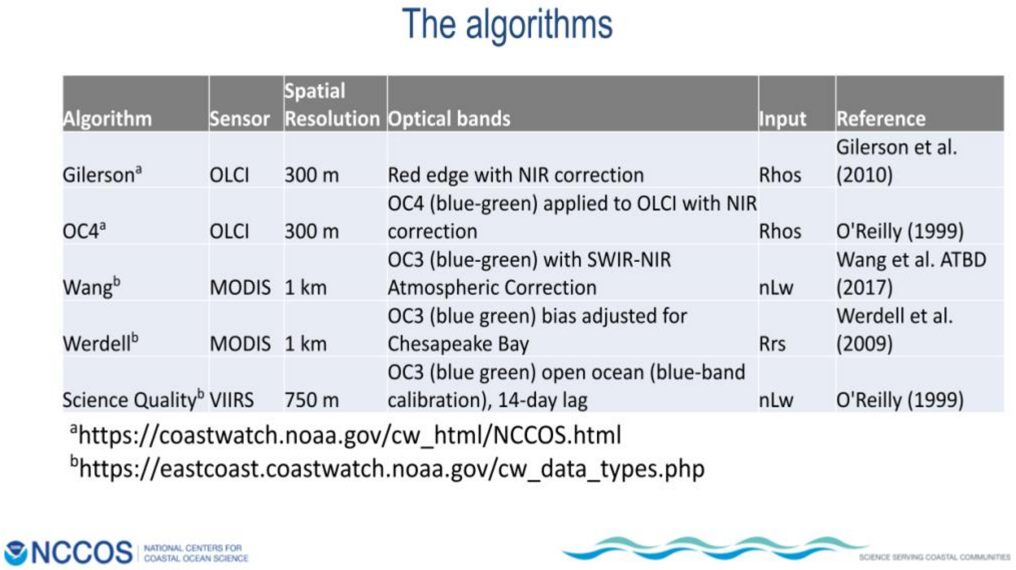
The present approach to the work used a R-tidymodels framework with Random Forest machine learning algorithms on the log transformation of chlorophyll *a* fluorescence (R Core Team, 2024). Cross validation (5 folds) was performed. Results of the applications are provided for diverse areas of the Chesapeake Bay tidal waters across the time series. While recent studies (e.g., He et al. 2021) have created a decade long Bay-wide assessment of chlorophyll *a* illustrating change over time, this work illustrates an example of the evolving capacity to create Bay-wide, satellite-based measures of chlorophyll *a* for the entire period of record involving the CBP monitoring program (1984-present). A preliminary assessment of status and trends was shown offering new resolution into documenting patterns in space and trends over time as never before available with chlorophyll *a* for this region.

NOAA satellite-based Chlorophyll *a* assessment for Chesapeake Bay: Evaluating the efficacy of five chlorophyll algorithms in the Chesapeake Bay (USA) for operational monitoring and assessment – *Michelle Tomlinson (NOAA),* Timothy Wynne, Rick Stumpf (NCCOS), Sachi Mishra, Andrew Meredith and Travis Briggs (CSS), Ron Vogel (NOAA CoastWatch); Presentation Slides

Satellite-based chlorophyll assessment continues to improve for the challenging conditions found in estuaries. NOAA has continued to champion product development while testing and developing algorithms applied to satellite resources with different sensors and sensor resolutions. Recent methods, outlined for Chesapeake Bay applications, included the following:

- A red-edge chlorophyll *a* algorithm was compared with 4 other algorithms (1 open ocean OC4 algorithm, and 3 operational algorithms delivered at CoastWatch East Coast Node).
- Algorithms varied by sensor, resolution, and satellite reflectance used.
- 38 Stations along the center of the Bay were selected for analysis.
- A median of a 3x3 pixel box surrounding the field sample was used in the analysis.
- All pixels at a station were extracted, and a time-series analysis was conducted to assess stability.
- The degree of agreement between field and satellite measures was evaluated using the multiplicative median bias and absolute error.

Five algorithms have been tested (Figure 23) with each providing image outputs through NOAA's Coastwatch website https://coastalscience.noaa.gov (Figure 24). Performance comparisons between field measures and algorithm-derived results and varied with all operational algorithms overestimating chlorophyll *a*. Due to resolution and atmospheric correction, less upper Bay pixels to work with in this assessment effort. Individual algorithm results included Gilerson falling along a 1:1 fit line providing the best fit with the least scatter. OC4 is underestimating chlorophyll *a.*



The algorithms

Algorithm	Sensor	Spatial Resolution	Optical bands	Input	Reference
Gilerson[a]	OLCI	300 m	Red edge with NIR correction	Rhos	Gilerson et al. (2010)
OC4[a]	OLCI	300 m	OC4 (blue-green) applied to OLCI with NIR correction	Rhos	O'Reilly (1999)
Wang[b]	MODIS	1 km	OC3 (blue-green) with SWIR-NIR Atmospheric Correction	nLw	Wang et al. ATBD (2017)
Werdell[b]	MODIS	1 km	OC3 (blue green) bias adjusted for Chesapeake Bay	Rrs	Werdell et al. (2009)
Science Quality[b]	VIIRS	750 m	OC3 (blue green) open ocean (blue-band calibration), 14-day lag	nLw	O'Reilly (1999)

[a]https://coastwatch.noaa.gov/cw_html/NCCOS.html
[b]https://eastcoast.coastwatch.noaa.gov/cw_data_types.php

NCCOS NATIONAL CENTERS FOR COASTAL OCEAN SCIENCE

SCIENCE SERVING COASTAL COMMUNITIES

Figure 23. *Algorithms tested for satellite-based chlorophyll a assessment in Chesapeake Bay.*

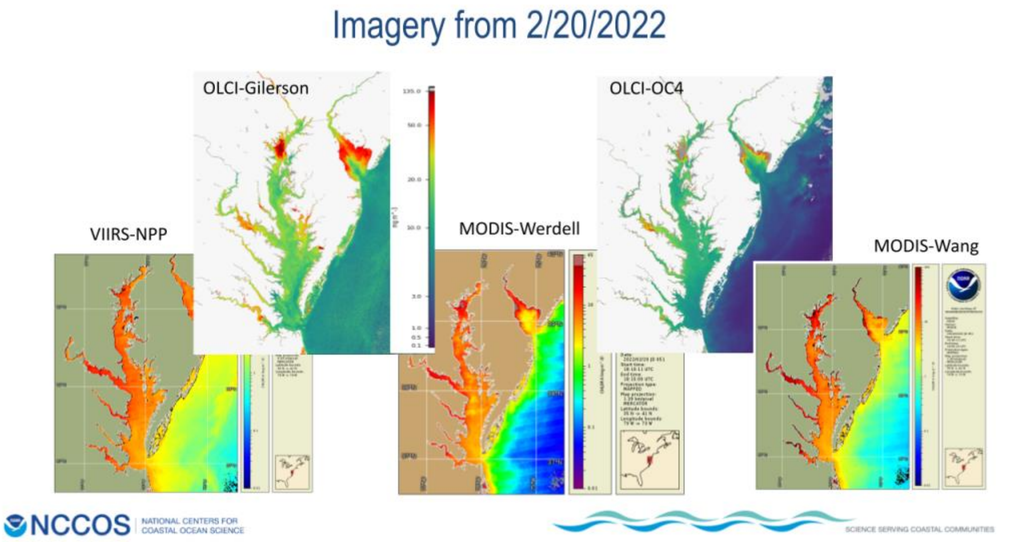
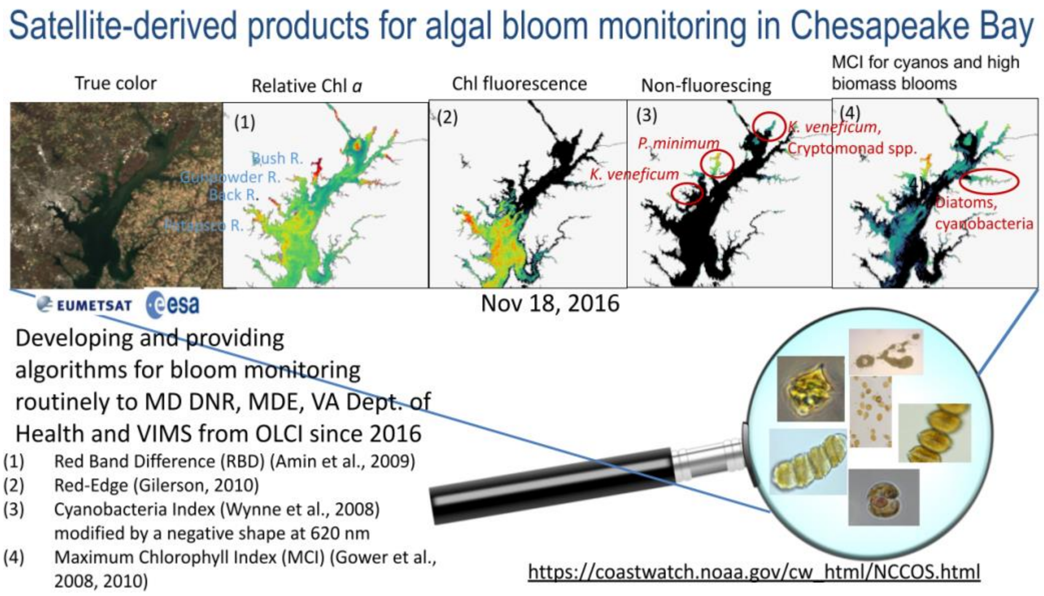


Figure 24. *Chlorophyll a maps developed using the 5 algorithms as applied to OCLI, VIIRS and MODIS imagery as appropriate.*

HABs are diverse in Chesapeake Bay with over a dozen toxigenic species and bloom records across species occupying all seasons. The narrative chlorophyll criteria for Chesapeake Bay jurisdictions (refer to USEPA 2003) are in need of a quantitative output characterizing HAB conditions (e.g., characterizing frequency, magnitude, duration, space and timing). NOAA continues to work on expanding capacity for quantitating HABs conditions using satellite-derived products (e.g., Wolny et al. 2020, and work presented here in the workshop show in Figure 25) offering new opportunities for support of chlorophyll *a* criteria assessment for the CBP community.



Satellite-derived products for algal bloom monitoring in Chesapeake Bay

Nov 18, 2016

Developing and providing algorithms for bloom monitoring routinely to MD DNR, MDE, VA Dept. of Health and VIMS from OLCI since 2016

(1) Red Band Difference (RBD) (Amin et al., 2009)
(2) Red-Edge (Gilerson, 2010)
(3) Cyanobacteria Index (Wynne et al., 2008) modified by a negative shape at 620 nm
(4) Maximum Chlorophyll Index (MCI) (Gower et al., 2008, 2010)

https://coastwatch.noaa.gov/cw_html/NCCOS.html

Figure 25. *NOAA Coastwatch progress with developing and providing algorithms for algal bloom monitoring in Chesapeake Bay.*

Dissolved Oxygen

Session 3. Advanced monitoring approaches to enhance tidal Chesapeake Bay habitat assessment dissolved oxygen, May 11, 2022.

Advanced Monitoring Focus: Overview on Dissolved Oxygen Criteria Attainment Assessment

Advanced monitoring and assessment approaches are necessary to fully assess water quality standards attainment in all 92 segments of Chesapeake Bay relevant to measuring and reporting on tidal water jurisdictional water quality standards. Dissolved oxygen criteria attainment assessment has been particularly limited by a lack of high temporal frequency water quality data collection in open-water and deep-water habitats to evaluate water quality standards attainment of applicable short-duration criteria (i.e., 7-day mean, 1-day mean, instantaneous minimum). The long-term Chesapeake Bay water quality monitoring network was designed in the 1980s to support annual and seasonal level assessments of status and trend in water quality measures in response to management interventions. The data demands of published dissolved oxygen criteria in the early 2000s, however, led to characterization of the network as “marginal” for assessing all scales of space and time defined by the then newly developed water quality criteria (USEPA 2003). “Recommended” levels of monitoring were envisioned as having vertical arrays or water quality profilers collecting high temporal density water quality measures for dissolved oxygen, salinity, and temperature at each of the 156 long-term water quality monitoring stations (USEPA 2003) supporting bay-wide evaluation of all criteria-relevant space- time scales.

Statistical methods that could serve to overcome the monitoring capacity limitations between ‘marginal’ and ‘recommended’ levels of monitoring data to support all the published DO space-time criteria information needs were evaluated and summarized in USEPA (2017). However, proposed methods were not adopted and codified by tidal bay jurisdictions for use in Chesapeake Bay water quality standards attainment assessments. Conditional attainment of multiple criteria, i.e., water quality measures at one scale informing attainment or nonattainment of criteria at another scale, was one of the methods addressed in USEPA (2017) and had its foundations recognized in USEPA (2004). The 2004 findings were expanded in the development in USEPA (2017) and were then applied to develop a multimetric water quality standards attainment indicator as a tracking tool of bay health (Hernandez-Cordero et al. 2020). To further fulfill the assessment needs of the CBP, new analysis methods and monitoring approaches were needed.

Three-dimensional interpolation using an inverse distance weighting algorithm was the first tool used to characterize water quality conditions related to newly published Chesapeake Bay dissolved oxygen criteria (USEPA 2003). However, four-dimensional (4D) interpolation was envisioned as the desired method for achieving the required analysis support to meet the CBP water quality criteria assessment needs. Curriero et al. (2008) evaluated the potential for having a 4D habitat tool and indicated the capacity to develop and apply a 4D tool for water quality characterization was not yet available.

Since 2008, new research and publications have demonstrated methods for more accurate dissolved oxygen assessments in estuaries including achieving space-time (4D) interpolation (e.g., Obenour et al. 2013, Matli et al. 2018, Matli et al. 2020). Further, a team of analysts in the CBP explored these advances in 2020-21 and evaluated the potential for application to dissolved oxygen tracking in Chesapeake Bay. Team findings were positive that conceptually and technically dissolved oxygen 4D assessment was now feasible and formed a new team, the CBP's Bay Oxygen Research Group (Bay Oxygen Research Group) for tool development.

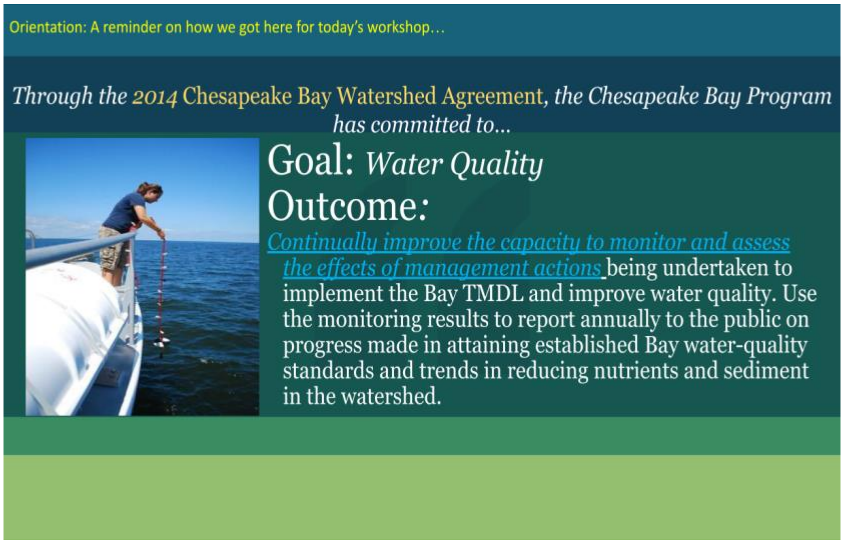
Coincidentally, publications of the past decade, (e.g., Bever et al. 2013, Bever et al. 2018) demonstrated that fewer high frequency vertical water quality measurements could provide the information needed to create as good or better assessments of habitat, specifically hypoxia impacted waters, than the 156-station program previously recommended. Peter Tango (USGS) and Bruce Vogt (NOAA) developed a competitive funding proposal to pilot study the use of new equipment with robust qualities to operate in the difficult conditions of the open waters in Chesapeake Bay. The awardee (Doug Wilson, Caribbean Wind LLC) successfully launched and managed extended deployments with new sensor packages that provided robust data collection for the water column in the open water habitats of Chesapeake Bay (Wilson 2019). The success of the pilot project led to a new Bay water quality monitoring-network development supported by a focus group, the Hypoxia Collaborative Team (Hypoxia Collaborative Team). The Hypoxia Collaborative Team was interested in improving Bay habitat monitoring and achieving high temporal frequency habitat dissolved oxygen monitoring in challenging, offshore, deep water Bay habitats.

Projects aimed at evolving the DO monitoring and analysis program could soon become operational to support DO criteria attainment assessments across diverse Bay habitats. Leaders involved in the state of the science presented current capacities, outputs of existing analyses, and project status toward the new phase of the Chesapeake Bay water quality interpolator. Explorations of additional methods for consideration on their applicability to DO monitoring and assessment needs were shared in this session.

Presentation Summaries on Session, Dissolved Oxygen

Overview of Workshop Content and Goals – *Peter Tango (USGS)*

This workshop received support with the understanding that the water quality standards attainment and monitoring goal in the 2014 Watershed Agreement (CBP 2014) was not fully supported in the CBP partnership (Figure 26). Monitoring capacity was highly stressed and declined during the 2010s where funding levels remained stable. Coincidentally, annual cost of living increases occurred due to inflation rates that varied from +0.7% to +3.0% per year over the decade. In response to the effect of rising costs that were unaccounted for in successive annual budgets, the situation forced strategic management choices in conducting the monitoring program by reducing data collections.



Orientation: A reminder on how we got here for today's workshop…

Through the 2014 Chesapeake Bay Watershed Agreement, the Chesapeake Bay Program has committed to…

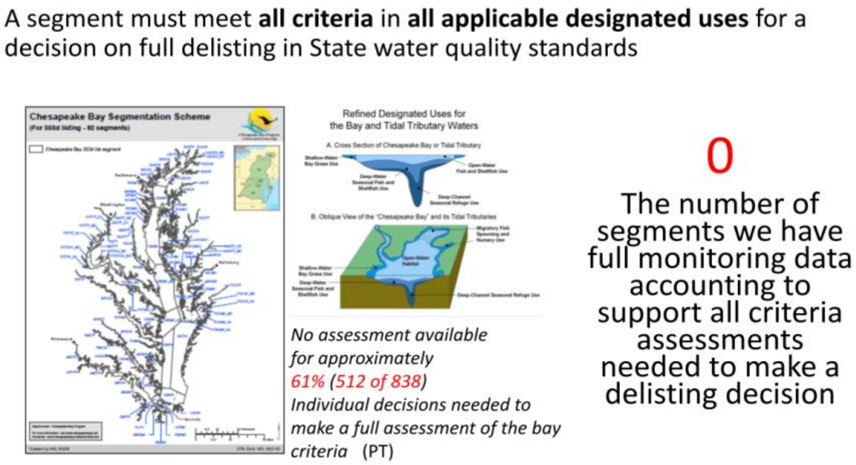
Goal: *Water Quality*

Outcome*:*

Continually improve the capacity to monitor and assess the effects of management actions being undertaken to implement the Bay TMDL and improve water quality. Use the monitoring results to report annually to the public on progress made in attaining established Bay water-quality standards and trends in reducing nutrients and sediment in the watershed.

Figure 26. *Water quality goal of the 2014 Chesapeake Watershed Agreement.*

Beyond declining data collections, insufficient monitoring capacity at time and space scales needed for a full water quality criteria assessment and limitations of tools to create the complete assessment had multiple impacts. First, no management segment in Chesapeake Bay could have all of its dissolved oxygen criteria assessed. Second, there was limited capacity for water clarity evaluations beyond the data generated by the SAV monitoring program. Third, monitoring program capacity designed for chlorophyll *a* status and trends assessment had low robustness for supporting a regulatory criteria evaluation needed for seasonal chlorophyll *a* assessments. The challenges meant that there was insufficient support to complete water quality standards attainment assessment based on the criteria adopted into state regulations for any segment in the history of the CBP to date (Figure 27). The complex dissolved oxygen criteria have been the most challenging for monitoring and assessment with short-duration criteria (instantaneous minimum) being poorly represented, and 1-day and 7- day means not being assessed at all with any method. Indirect, probability-based assessment method options were published in USEPA (2017) but have not been implemented to date.



A segment must meet **all criteria** in **all applicable designated uses** for a decision on full delisting in State water quality standards

No assessment available for approximately 61% (512 of 838) Individual decisions needed to make a full assessment of the bay criteria (PT)

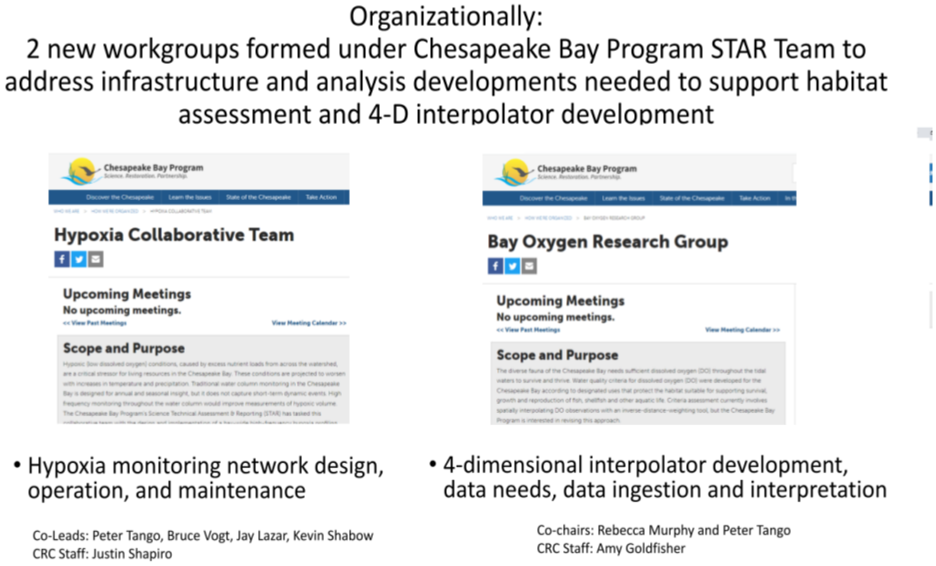
0

The number of segments we have full monitoring data accounting to support all criteria assessments needed to make a delisting decision

Figure 27. *Summary of Chesapeake Bay Program gap in assessing water quality criteria related to the 2014 Chesapeake Bay Watershed Agreement (CBP 2014) and 2010 Chesapeake Bay Total Maximum Daily Loads (USEPA 2010) expectations.*

4-dimensional interpolation was highlighted as a need to support the assessment of the full suite of dissolved oxygen criteria. The capacity to address this need was evaluated by a CBP STAC panel (Curriero et al. 2008) concluding with a consensus opinion that the sampling frequency and spatial resolution of the existing Chesapeake Bay datasets are insufficient for successful extrapolation to four dimensions. In 2021, however, an on-going effort among Chesapeake Bay partners to acquire funding to deploy continuous monitoring buoys was underway. The buoy systems are equipped with vertical arrays of sensors and can collect data throughout the water column in deep water areas of the Chesapeake Bay and tidal tributaries. Curriero et al. (2008) envisioned that if such efforts as those invested in with the new buoys to improve data collections succeed, "then the shortcomings of existing datasets will be greatly alleviated."

Organizationally, the Hypoxia Collaborative Team and Bay Oxygen Research Group groups have been formed in the CBP to address support for overcoming dissolved oxygen monitoring and criteria assessment challenges (Figure 28). Capacity for data collection needs increased as a result of a pilot study that successfully addressed the data issues: a 2018-19 Goal Implementation Team Funded Pilot Project on robust, cost-effective high frequency water quality profiling data collection (Wilson 2019). The 4D interpolator tool development has been guided by a conceptual framework (Figure 29).



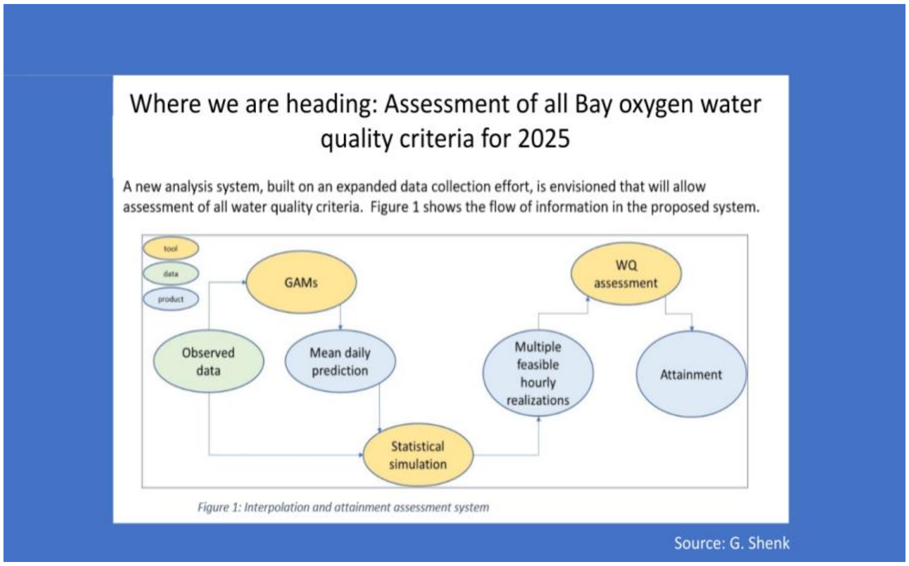
Organizationally:
2 new workgroups formed under Chesapeake Bay Program STAR Team to address infrastructure and analysis developments needed to support habitat assessment and 4-D interpolator development

- Hypoxia monitoring network design, operation, and maintenance
- 4-dimensional interpolator development, data needs, data ingestion and interpretation

Co-Leads: Peter Tango, Bruce Vogt, Jay Lazar, Kevin Shabow
CRC Staff: Justin Shapiro

Co-chairs: Rebecca Murphy and Peter Tango
CRC Staff: Amy Goldfisher

Figure 28. *Chesapeake Bay Program Workgroups providing support for overcoming habitat assessments with new tools and new data collection capacities.*



Where we are heading: Assessment of all Bay oxygen water quality criteria for 2025

A new analysis system, built on an expanded data collection effort, is envisioned that will allow assessment of all water quality criteria. Figure 1 shows the flow of information in the proposed system.

Figure 1: Interpolation and attainment assessment system

Source: G. Shenk

Figure 29. *4D interpolator framework for addressing water quality criteria attainment.*

The programmatic issues with monitoring and analysis highlighted in the presentation represented three themes being addressed in the session:

- Dissolved oxygen criteria assessment – present and future.
- Tool development – the 4D water quality interpolator, and
- Advanced Monitoring – directions on expanding the monitoring program data collections to fill gaps in data necessary to conduct a full accounting of water quality conditions as outlined in state regulations for Chesapeake Bay habitats.

Existing Dissolved Oxygen Criteria Assessment for Chesapeake Bay – *Richard Tian (UMCES), Qian Zhang (UMCES) and Peter Tango (USGS)*

The following key points were highlighted in this overview describing the existing dissolved oxygen criteria assessment approach for the Chesapeake Bay habitats:

- Data are interpolated across a grid with a 3D interpolator tool to address spatial gaps in the monitoring design.
- Inverse distance weighting (IDW) is used for the interpolation procedure.
- Data at each point are linearly interpolated in the vertical plane.
- Data are then interpolated in the horizontal plane.
- Salinity and temperature data are used to define the presence of pycnocline layers that establish designated use boundaries.
- Interpolated data are summarized in a cumulative frequency distribution (CFD) plot and compared against a 10% space-time reference curve or a bio reference curve (if available).
- Any evidence of non-attainment means the segment fails to meet the criterion being evaluated, otherwise, the segment evaluation for an applicable season and designated use meets healthy conditions for the measure evaluated.
- To date, summer season 30-day mean open water dissolved oxygen criteria and instantaneous minimum deep-water criteria are being evaluated. Other duration criteria (e.g., 1-day and 7-day means) as well as other habitats (e.g., migratory spawning) and seasons are unassessed.

Future Criteria Assessment Protocol Framework Addressing All Time Scales of Chesapeake Bay Dissolved Oxygen Criteria – *Gary Shenk (USGS)*; Presentation Slides

A new framework to support assessment of all Chesapeake Bay dissolved oxygen criteria has been developed that recognizes the new high temporal frequency dissolved oxygen data availability from the evolving hypoxia monitoring network. This new framework complements the existing workflow of the existing criteria assessment process and builds on the process for this expanded application to evaluate water quality criteria attainment with output from a 4-D interpolator. The 4-D interpolator is under development.

Data needs to address the full needs expected to complete the existing criteria assessments published in USEPA (2003) and adopted into State regulations have been constrained by a sampling program that has bay-wide coverage but only collects 1 to 2 samples per month at each station. The existing monitoring program was designed and implemented in 1985 to support seasonal and annual status and trends long before the Bay water quality criteria were developed and assessment methods designed. Working with existing data available from the long-term water quality monitoring program, a 30-day mean, for example, has been estimated by either a single monthly value, or the average of 2 values. Instantaneous minimum criterion assessment further relies on 1 to 2 values per month; however, if hourly measures were considered, there could be a more robust evaluation of habitat with a monthly sum of over 600 observations.

The present methods rely on habitat assessment that focuses on interpretation from the direct measurements. The future of water quality assessment generated by the new 4D tool under development is expected to include a probability-based evaluation of water quality criteria (Figure 30). The framework under development starts with our observed data that cover space and time scales representing all the dissolved oxygen criteria. The method selected for interpolation is generalized additive models (GAMs). The data run through a GAMs protocol are presently targeted to provide mean daily predictions of conditions.

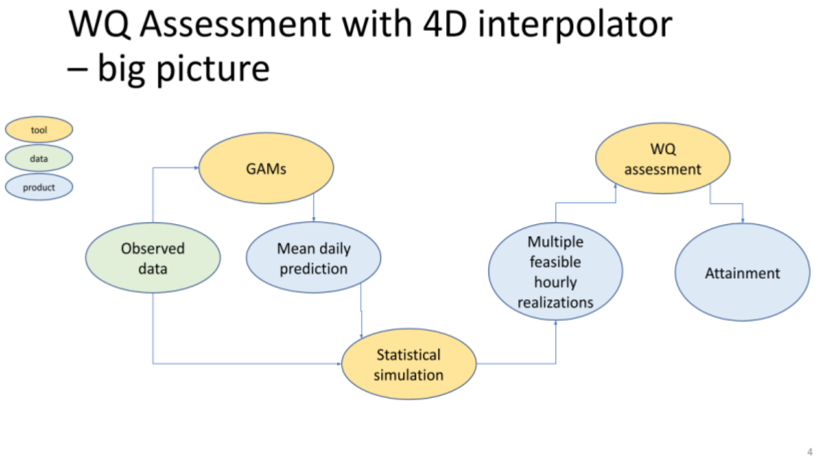
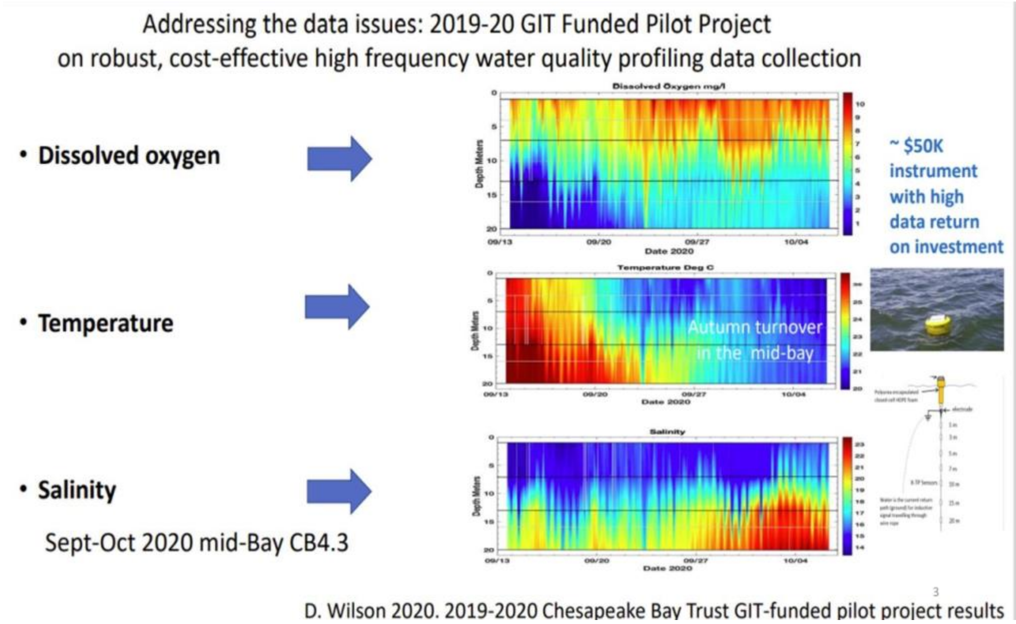


Figure 30. *The 4D interpolator framework for the future Chesapeake Bay criteria attainment assessment.*

The newest data addressing gaps for assessing short duration dissolved oxygen criteria (i.e., instantaneous minimum, 1-day mean, 7-day mean) are generated by deployments of robust vertical monitoring arrays capable of collecting high temporal frequency water quality data in previously difficult habitats for monitoring (example provided in Figure 31). Bever et al. (2013, 2018), indicated effective hypoxia monitoring can be achieved with as few as 2 vertical arrays strategically located in the mainstem of Chesapeake Bay. Recent investments aim to create an array network to support data needs required of the criteria assessment involving the bulk quantity of hypoxia and its spatial distribution through time.



Addressing the data issues: 2019-20 GIT Funded Pilot Project
on robust, cost-effective high frequency water quality profiling data collection

- **Dissolved oxygen**
- **Temperature**
- **Salinity**

Sept-Oct 2020 mid-Bay CB4.3

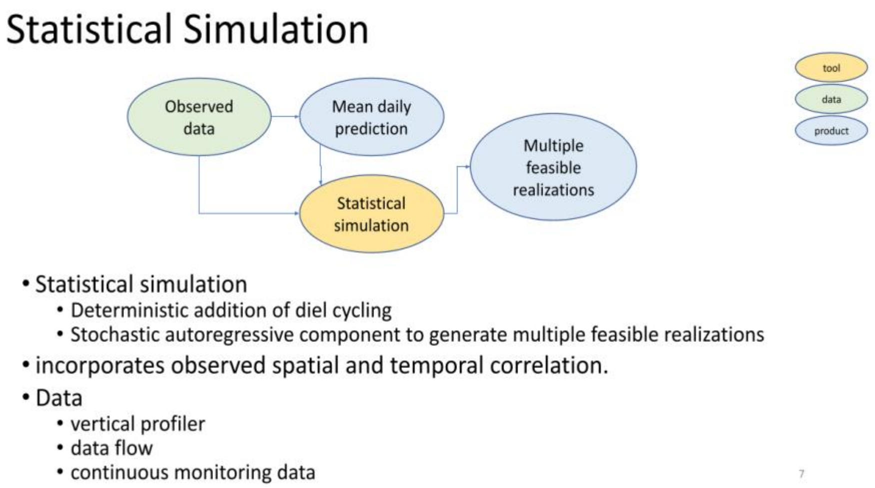
~ $50K instrument with high data return on investment

Autumn turnover in the mid-bay

D. Wilson 2020. 2019-2020 Chesapeake Bay Trust GIT-funded pilot project results

Figure 31. *Pilot project data results from 2019-2020 showing the water column water quality using a robust, easily deployable and retrievable, cost-effective sensor array for water quality monitoring in open water habitats of Chesapeake Bay.*

Updated methods of assessment are being designed to include the use of statistical simulations of parameter conditions of the designated use or habitat. Statistical simulation is being built upon understanding of water quality behavior from multiple data sources (e.g., long-term water quality monitoring program data, data flow data, vertical array time series) and applied to produce multiple hourly realizations that support the mean daily prediction of habitat conditions (Figure 32). The distribution of mean daily predictions will provide an output on probability of habitat meeting its criterion for the applicable period necessary under the definition of the designated use.

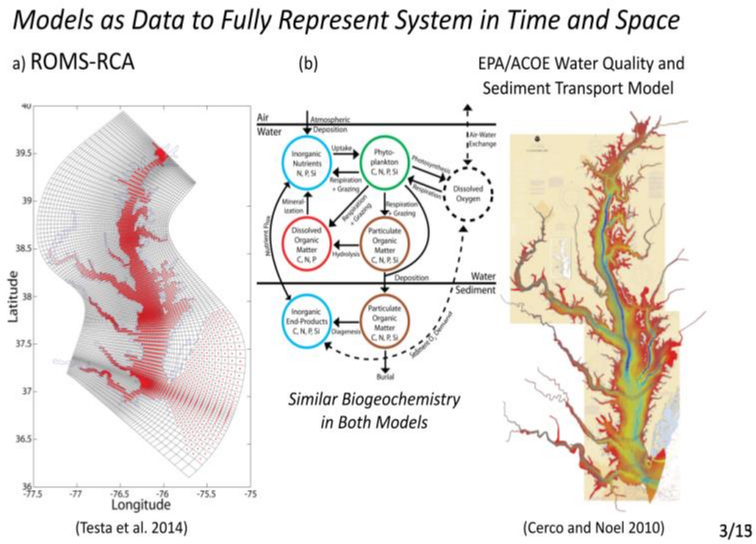


Statistical Simulation

- Statistical simulation
  - Deterministic addition of diel cycling
  - Stochastic autoregressive component to generate multiple feasible realizations
- incorporates observed spatial and temporal correlation.
- Data
  - vertical profiler
  - data flow
  - continuous monitoring data

Figure 32. *Outline of the statistical simulation supporting water quality assessment in the 4D interpolator tool under development from 2022-2025 at the Chesapeake Bay Program.*

Options for Assessing Dissolved Oxygen Criteria – *Dong Liang (UMCES*; [Presentation Slides](#)
University of Maryland Center for Environmental Studies scientists have been working on evaluating spatial sampling design to improve water quality criteria attainment assessment efficiency based on numerical simulations. This approach is being applied to evaluate options for dissolved oxygen criteria assessment in tidal waters of Chesapeake Bay to address the full range of time-dependent management criteria found in estuarine water quality standards for the Bay (i.e., instantaneous minimum, 1- day mean, 7- day mean, 30-day mean) (Figure 33 and 34).



Models as Data to Fully Represent System in Time and Space

a) ROMS-RCA

(b)

EPA/ACOE Water Quality and Sediment Transport Model

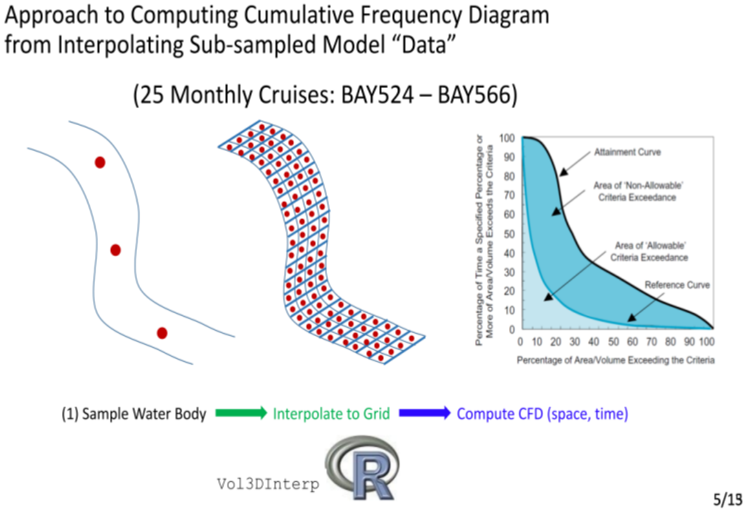
Similar Biogeochemistry in Both Models

(Testa et al. 2014)

(Cerco and Noel 2010)

3/13

Figure 33. *Framework for conducting numerical simulations and assessments of monitoring options for assessing uncertainty in dissolved oxygen criteria evaluations for Chesapeake Bay.*



Approach to Computing Cumulative Frequency Diagram from Interpolating Sub-sampled Model "Data"

(25 Monthly Cruises: BAY524 – BAY566)

(1) Sample Water Body → Interpolate to Grid → Compute CFD (space, time)

Vol3DInterp

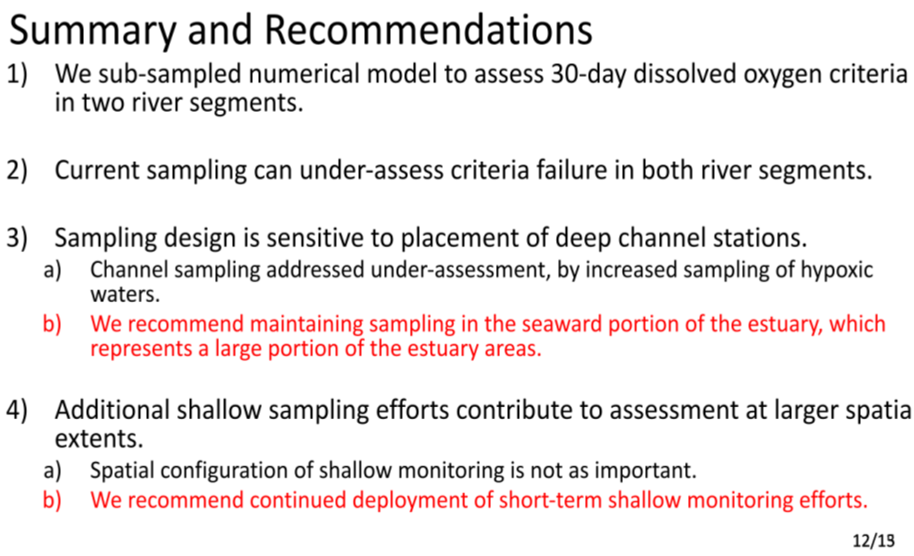
5/13

Figure 34. *Envisioning the approach to evaluating a model-based approach for evaluating monitoring design effects on uncertainty and bias in estimating field conditions for dissolved oxygen criteria attainment following methods used by States as outlined in USEPA (2003) for Chesapeake Bay.*

The following summary of work described in the presentation borrows from the Liang et al. (2022) publication upon which the presentation was organized, *A hydrodynamic model–based approach to assess sampling approaches for dissolved oxygen criteria in the Chesapeake Bay,* described in the journal Environmental Monitoring and Assessment:

> "*Technological advances in water quality measurement systems have provided the potential to expand high-frequency observations into coastal monitoring programs. However, with limited resources for monitoring budgets in natural waters that exhibit high temporal and spatial variability in water quality, there is a need to identify the locations and time periods where these new technologies can be deployed for maximum efficacy. To advance the capacity to make quantitative and objective decisions on the selection of monitoring locations and sampling frequency, we combined high-resolution numerical model simulations and multi-frequency water quality measurements to conduct a power analysis comparing alternative sampling designs in the assessment of water quality in the Chesapeake Bay. Specifically, we evaluated candidate monitoring networks that deployed both conventional long-term fixed station monitoring in deep channel areas and short-term continuous monitoring technologies in near-shore, shallow areas to assess 30-day dissolved oxygen criteria in two Bay tributaries. We conducted a cumulative frequency diagrams analysis to quantify the accuracy of each monitoring scheme in evaluating compliance with respect to the model. We used a Monte Carlo simulation to incorporate the spatial and temporal uncertainty of criteria failure. We found that additional long-term biweekly channel and short-term continuous shallow sampling efforts can lead to statistically unbiased and improved assessments at local spatial extents (less than 0.2 proportion of the assessed water body), especially when additional sampling is added at stations representing hypoxic water areas. Stations that represented seaward regions of the tributaries were more valuable in maintaining unbiased assessments of dissolved oxygen criteria attainment. The analysis highlights the importance of statistical evaluation of ongoing monitoring programs and suggests an approach to identify efficient deployments of monitoring resources and to improve assessment of other water quality metrics in estuarine ecosystems.*"

Findings of the work offered guidance for consideration by CBP partners designing segment assessments of habitat conditions when applying multiple sensor deployments in support of data collection needs and criteria attainment evaluations (Figure 35).



Summary and Recommendations

1) We sub-sampled numerical model to assess 30-day dissolved oxygen criteria in two river segments.

2) Current sampling can under-assess criteria failure in both river segments.

3) Sampling design is sensitive to placement of deep channel stations.
   a) Channel sampling addressed under-assessment, by increased sampling of hypoxic waters.
   b) We recommend maintaining sampling in the seaward portion of the estuary, which represents a large portion of the estuary areas.

4) Additional shallow sampling efforts contribute to assessment at larger spatial extents.
   a) Spatial configuration of shallow monitoring is not as important.
   b) We recommend continued deployment of short-term shallow monitoring efforts.

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Figure 35. *Summary slide from Dong Liang's (UMCES).*

Considerations for the Design of the 4D Water Quality Interpolator – *Rebecca Murphy (UMCES)*; Presentation Slides

The diverse fauna of the Chesapeake Bay needs sufficient dissolved oxygen (DO) throughout the tidal waters to survive and thrive. Water quality criteria for dissolved oxygen (DO) were developed for the Chesapeake Bay according to designated uses that protect the habitat suitable for supporting survival, growth and reproduction of fish, shellfish and other aquatic life. To date, CBP partners conduct criteria assessments by spatially interpolating habitat conditions (e.g., DO observations) with an inverse-distance-weighting tool (refer to presentation by B. Romano and M. Trice (2013) for a summary of the tool and its specifications at https://d38c6ppuviqmfp.cloudfront.net/channel_files/19317/m._trice_-_using_the_chesapeake_bay_program_interpolator_(part_1).pdf). However, the CBP is interested in updating this approach.

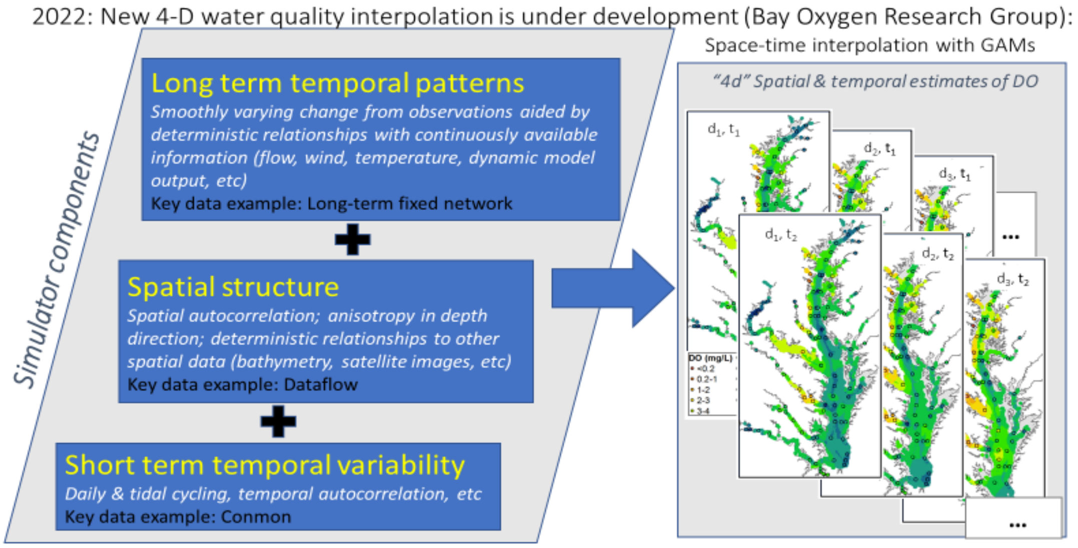
A 2008 STAC panel report findings suggested a set of functional requirements necessary for development of a 4-D Interpolator to address assessment capacity evaluating the suite of published criteria used in protection of Bay living resources (Curriero et al. 2008). The STAC panel highlighted requirements for using a 4-D interpolator for water quality impairment status assessment as described here:

1. The interpolated fields should allow evaluation of a 1-day mean, a 7-day mean, and a 30-day mean. Because of the importance of tidal and advective circulation motions for dissolved oxygen variability, temporal resolution of the data needs to be at least two measurements per tidal cycle.
2. Interpolated values should be accompanied by statistical estimates of uncertainty.
3. Functionality must exist to automate the interpolation process, eliminating the need for subjective "expert" decisions that are manually implemented at various stages of interpolation. Expert knowledge will go into developing, maintaining, and updating the interpolation scheme.

4. Interpolation must be unbiased with respect to the data and capable of "filling in the gaps" between monitoring data.
5. Interpolated parameters include at least dissolved oxygen, and preferably chlorophyll *a* concentration and water clarity.
6. The interpolator must recognize land boundaries and not interpolate across land.
7. The interpolation method adopted by the CBP should be based on approaches with a sound scientific basis that are supported by studies in the peer-reviewed scientific literature.
8. The properties of the chosen interpolation method that identify it as the optimal method for the intended application should be characterized.

The consensus of the 2008 expert panel was that there was insufficient science information to support the feasibility of creating a 4-D interpolator for use in water quality assessment.

The CBP Bay Oxygen Research Group (BORG) was formed in 2020 to examine progress made in research, development and applications with 4D water quality assessments, review the new science and evaluate options for viability and feasibility. The BORG agreed on the feasibility to advance tool development for creating a new phase of the water quality interpolation tool beyond the 3D version in use by CBP to generate dissolved oxygen (DO) (i.e., habitat) condition estimates across space and through time. The new interpolator would improve upon the current spatial interpolation used in the Chesapeake Bay (Figure 36).



Smoothly varying change from observations aided by deterministic relationships with continuously available information (flow, wind, temperature, dynamic model output, etc)

Key data example: Long-term fixed network

Spatial autocorrelation; anisotropy in depth direction; deterministic relationships to other spatial data (bathymetry, satellite images, etc)

Key data example: Dataflow

Daily & tidal cycling, temporal autocorrelation, etc

Key data example: Conmon

Source: R. Murphy

Figure 36. *Considerations in the structure and function of the new CBP 4D interpolator tool for criteria attainment assessment.*

The planned structure of the tool is for using water quality observations, interpolating with the use of GAMs, and simultaneously addressing long-term and short duration temporal water quality patterns, as well as spatial data structure, within a simulation framework. The output of the tool will, for the first time, allow for expanded evaluation of short-duration criteria (i.e., instantaneous minimum, 1-day mean, 7- day mean) using new and current data streams and aid in habitat assessments. The group will focus on development of the initial phase of the tool from 2021 to 2025 before advancing work on application and education in the following years (2026+).

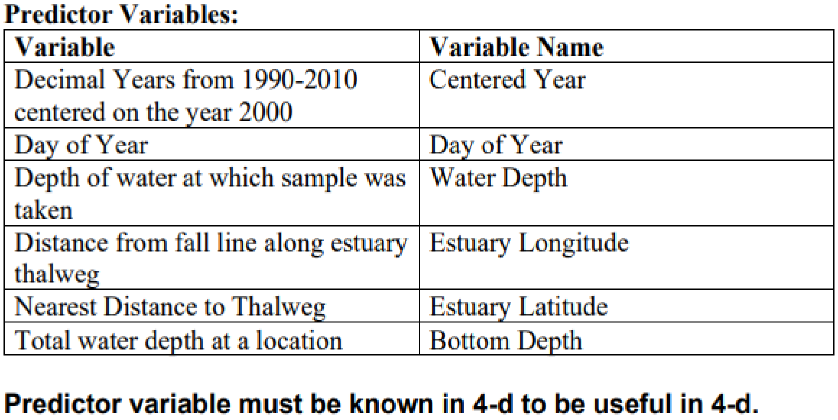
New needs for the 4D interpolator compared with the existing Bay interpolator identified in the early stages of the work were:

- Temporal interpolation instead of snapshots in time.
- Output at a temporal and spatial level to assess short-term criteria.
- Output that can aid in habitat assessments.
- Uncertainty in the predictions (at least for diagnostics).
- Incorporation of more available data streams & types than the existing interpolator used by CBP.

A Trial Run of 4-D interpolation of Dissolved Oxygen Using Generalized Additive Models (GAMs) — *Elgin Perry, (Statistician)*; Presentation Slides

Development of a Chesapeake Bay 4D water quality interpolator is in its earliest phase of development. Parameters to include in developing the estimator for dissolved oxygen conditions needed to be variables that must be known in four dimensions. Table 6 highlights the fundamental parameters needed for building a GAM for Chesapeake Bay dissolved oxygen. The list of variables yet to be considered during the early GAM development included 1) watershed river flow (with appropriate lags), 2) pycnocline, 3) wind, 4) temperature and 5) tide. Other ideas for supporting development and tuning of the DO GAM include diagnostics involving outlier scrutiny, applying a Kalman Filter for improving interpolation, and cross-validation testing.

Table 6. *Initial variables loaded into the developmental Generalized Additive Models model for predicting daily mean dissolved oxygen.*



Predictor Variables:

Variable	Variable Name
Decimal Years from 1990-2010 centered on the year 2000	Centered Year
Day of Year	Day of Year
Depth of water at which sample was taken	Water Depth
Distance from fall line along estuary thalweg	Estuary Longitude
Nearest Distance to Thalweg	Estuary Latitude
Total water depth at a location	Bottom Depth

Predictor variable must be known in 4-d to be useful in 4-d.

The test region for the early development of the interpolator is the mid-Bay region, a region with a long history of data collection and study (Figure 37). Data collection has been in progress annually since 1985.

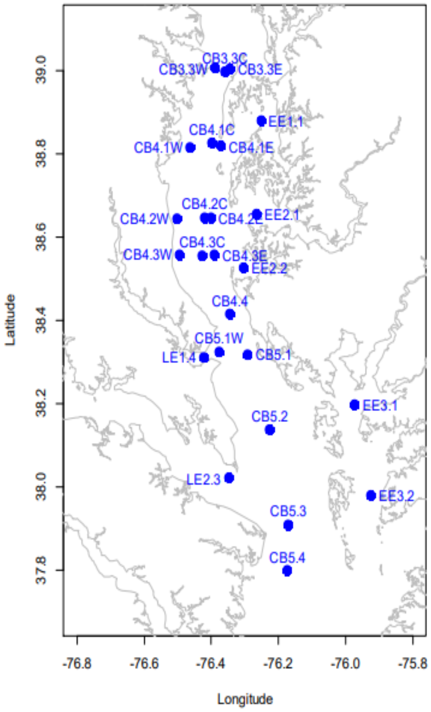
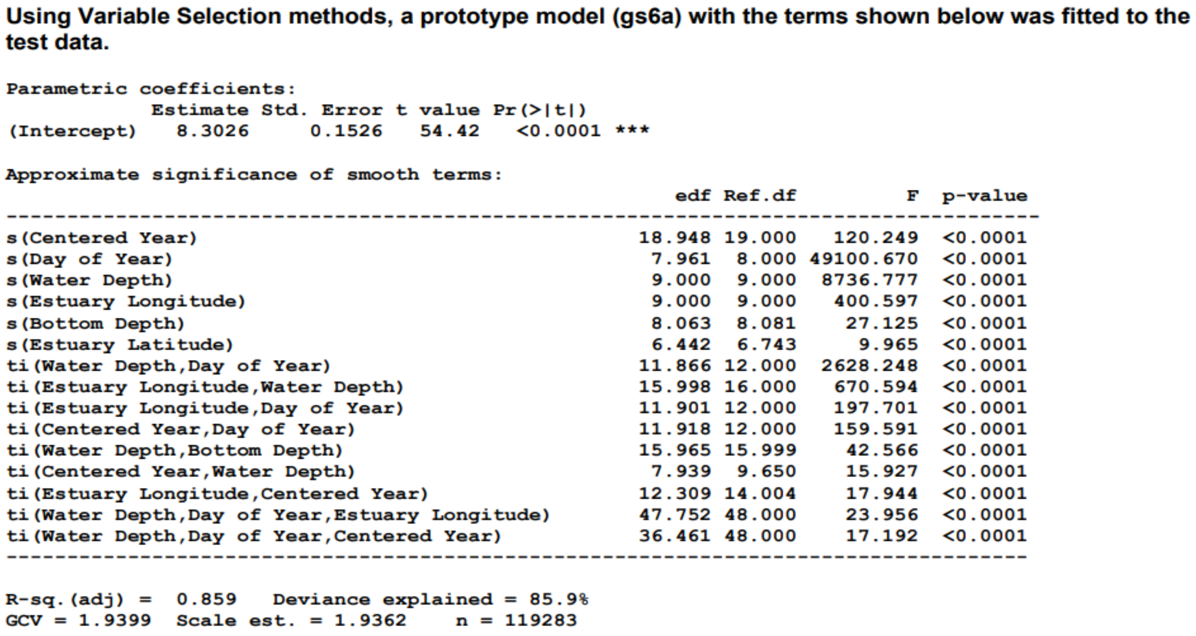


Figure 37. *Map of the middle Chesapeake Bay region and long-term Chesapeake Bay water quality monitoring stations used in the developmental phase of the 4D interpolator.*

The first prototype GAM model of dissolved oxygen applied in four dimensions was developed using a variable selection method fitted to long-term Chesapeake Bay water quality monitoring data. The results of the model explained 85.2% of the variance in dissolved oxygen behavior. (Table 7).

Table 7. *Prototype Generalized Additive M model with fitting results for the early development of the 4D interpolator construct.*



Using Variable Selection methods, a prototype model (gs6a) with the terms shown below was fitted to the test data.

```
Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   8.3026     0.1526   54.42   <0.0001 ***

Approximate significance of smooth terms:
                                                       edf Ref.df          F  p-value
-------------------------------------------------------------------------------------
s(Centered Year)                                    18.948 19.000    120.249  <0.0001
s(Day of Year)                                       7.961  8.000 49100.670  <0.0001
s(Water Depth)                                       9.000  9.000   8736.777  <0.0001
s(Estuary Longitude)                                 9.000  9.000    400.597  <0.0001
s(Bottom Depth)                                      8.063  8.081     27.125  <0.0001
s(Estuary Latitude)                                  6.442  6.743      9.965  <0.0001
ti(Water Depth,Day of Year)                         11.866 12.000   2628.248  <0.0001
ti(Estuary Longitude,Water Depth)                   15.998 16.000    670.594  <0.0001
ti(Estuary Longitude,Day of Year)                   11.901 12.000    197.701  <0.0001
ti(Centered Year,Day of Year)                       11.918 12.000    159.591  <0.0001
ti(Water Depth,Bottom Depth)                        15.965 15.999     42.566  <0.0001
ti(Centered Year,Water Depth)                        7.939  9.650     15.927  <0.0001
ti(Estuary Longitude,Centered Year)                 12.309 14.004     17.944  <0.0001
ti(Water Depth,Day of Year,Estuary Longitude)       47.752 48.000     23.956  <0.0001
ti(Water Depth,Day of Year,Centered Year)           36.461 48.000     17.192  <0.0001
------------------------------------------------------------------------------------

R-sq.(adj) =  0.859   Deviance explained = 85.9%
GCV = 1.9399  Scale est. = 1.9362    n = 119283
```

Given a conceptual model for environmental drivers affecting dissolved oxygen dynamics that considers factors affecting oxygen distribution beyond those initially loaded into the model (e.g., flow has multiple effects in the estuary, hydraulic effect operates at the scale of hours to days, delivery effect impacts the bay at scales of days to weeks, and food web effect operates on a scales of months) the first attempts to improve model performance added river flow and chronological time components. The improvement in explanatory ability was small, i.e., from 85.2% with no flow and no time in the model, 85.9% with time parameter added, and 86.7% with flow and time added to the initial model. The findings suggested that the initial model is very robust and captures a lot of the variation in DO behavior in the mid-bay region for daily means model without unnecessarily overcomplicating the model with additional parameters.

Work will continue to test model development in other bay and tributary regions, and to address the sub-daily dynamics of dissolved oxygen.

Investment in New Hypoxia Monitoring Network — *Peter Tango (USGS), Bruce Vogt (NOAA), Jay Lazaar (NOAA) and Kevin Shabow (NOAA)*

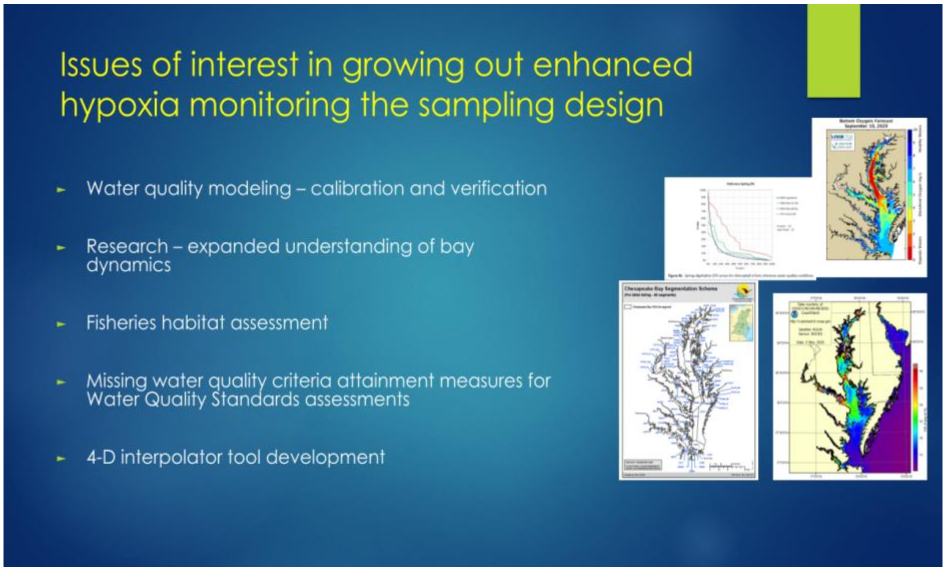
On March 2, 2021, the Principal Staff Committee (PSC) was provided with a presentation about the status of our water quality monitoring network. The PSC heard from EPA that the water quality monitoring program was characterized as “Fair” for addressing water quality criteria attainment assessments, technically insufficient to assess all criteria associated with water quality standards under the umbrella of the Chesapeake Bay TMDL. The largest gap involved assessing short duration dissolved oxygen criteria (USEPA 2003).

USEPA (2003) defined three levels of monitoring capacity for assessing dissolved oxygen criteria: Recommended, Adequate (or Good) and Marginal (or Fair). The 'Recommended' level of monitoring for dissolved oxygen criteria attainment has been expected to address bay-wide conditions each year involving all four frequencies of dissolved oxygen criteria (30-day mean, 7-day mean, 1-day mean, and instantaneous minimum) in all applicable seasons. The current fixed station monitoring program is designed to provide a long-term record of dissolved oxygen concentrations that reflect seasonal and interannual variation. For that reason, even though instantaneous measurements are collected, the current monitoring is best suited for assessing the 30-day mean dissolved oxygen criteria component and poorly suited for assessing the 7-day mean, 1-day mean, and instantaneous minimum criteria components. To address the need for data that will address the 7-day and, 1-day mean and instantaneous minimum criteria, "Recommended" implementation procedures components suggest continuous monitors mounted to buoys or piers will be required. At least one continuous monitor should be located at each assessment location. Individual criteria component estimates would be assessed at all fixed locations (n=156) and interpolated for incorporation in a cumulative frequency distribution assessment of habitat status.

Monitoring resources are insufficient to operate a program at the "recommended" level. "Fair" is equivalent to USEPA (2003) "marginal" characterization of monitoring program capacity to address regulatory criteria assessment needs of the community. Marginal monitoring assumes funding will not be available for even the 'adequate' level of monitoring; assessments would need to rely on the fixed-station data only. As stated above, this type of monitoring was designed for long-term assessments and would only be truly appropriate for the 30-day mean criteria component. With the 'marginal' level of monitoring, higher frequency criteria components have not been assessed in most designated use areas.

A "good" program would be equivalent to the program defined as "Adequate" monitoring design under USEPA (2003) characterization of monitoring program effort. Assuming that funding will not be available for the 'recommended' monitoring approach, the compromise would be to place a limited number of continuous monitors at representative locations in the Chesapeake Bay and tidal tributaries. The number of continuous monitors would be relatively small, but the number would be established to characterize different types of settings in Chesapeake Bay. Those representative temporal records have been envisioned to be combined with fixed-station data in similar settings for interpolation. The authors of USEPA (2003) considered a grand interpolation from the few stations with the potential need to accept high uncertainty. Considerations with small numbers of sensor arrays, however, may be to use such monitoring infrastructure in a rotational sampling design where segments of interest have high density observations to improve interpolations in the region(s) of most interest while uncertainties are larger in areas of lesser importance to the period of assessment.

Many groups are interested in improving habitat assessment and thus the development and growth of the hypoxia monitoring network (Figure 38). Sampling design considerations were provided by workgroups with diverse interests. Results of the community survey were folded into a target number of monitoring arrays that represent the "small number" referred to by the authors of the monitoring design recommendations highlighting an 'adequate' (i.e., good) level of resource investment (p. 178, USEPA 2003) to support monitoring needs addressing short duration habitat conditions.



Issues of interest in growing out enhanced hypoxia monitoring the sampling design

- Water quality modeling – calibration and verification
- Research – expanded understanding of bay dynamics
- Fisheries habitat assessment
- Missing water quality criteria attainment measures for Water Quality Standards assessments
- 4-D interpolator tool development

Figure 38. *Diverse Chesapeake Bay Program interests support the development, establishment and growth of the hypoxia monitoring network.*

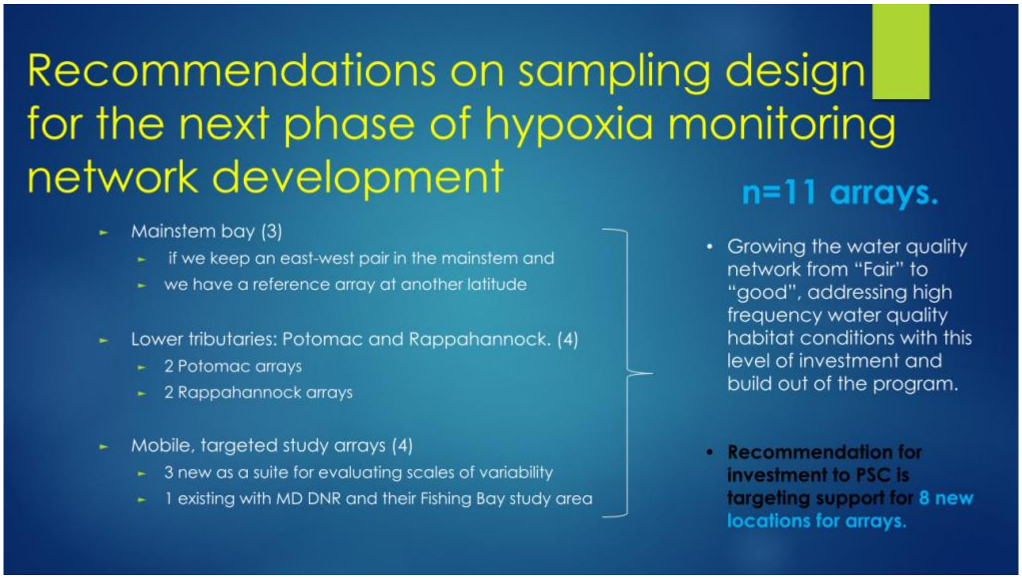
Input was requested from CBP workgroups and agencies involved in tidal bay monitoring regarding priority areas for near-term enhanced data collection. Considerations were first derived from suggestions that supported the funding for piloting a new array system with the GIT 2019-2020 project in the first place **-** analyses in the literature (Bever et al. 2013, Bever et al. 2018) have suggested as few as 2 arrays can be valuable assets to support improved hypoxia tracking in Chesapeake Bay. This information established the foundation for CBPs needs assessment. Further, there are focus areas planned for intensive monitoring (e.g., MD DNR Case Study Fishing Bay – shallow deployment array) and NOAA purchasing and deploying 2 vertical arrays. *Recommended deployment locations of these 2 arrays were recommended by the community for the east and west side of the middle of the mainstem bay.* The combination of existing instrumentation equaled 3 instruments available.

The CBP Modeling Workgroup provided further input: Having one or two reference arrays would be valuable. *Note: A reference instrument* may have 1 sensor per meter as a high-resolution vertical data collection from which other instruments would be able to key off of when we use fewer sensors to obtain the vertical water column structure. Reference instruments will obviously have a higher cost with more sensors. *Guidance provided by the workgroup was to consider at least 1 reference unit deployed in the Bay as part of the hypoxia monitoring resource portfolio would be reasonable and appropriate.*

The CBP monitoring community recognized the need for some available sensor arrays to be mobile to support data collections that inform understanding about spatial scales of water quality variability in local areas. This information was deemed valuable, for example, to inform the 4D interpolation algorithms about spatial variance structures in the data. Guidance provided by the monitoring community *recommended a suite of 3 instruments that is available for case study evaluations on scales of spatial variability in fish habitat/water quality.*

Suggestions from the Hypoxia Collaborative Team, with support from BORG 4-D Interpolator Team and the CBP Fisheries community, rounded out survey input on initial investment and initial distribution of instruments in the water. Uncertainty is recognized as high in areas of recurring hypoxia. It is important to move us outside of the mainstem. The Lower Potomac River is a high priority area for monitoring water quality and fisheries habitat, highlighted by our water quality analysts and modelers, and has multistate interests. The Lower Rappahannock River was given high priority for the same reasons. Therefore, the Hypoxia Collaborative team provided guidance recommending *2 arrays each in the lower Potomac River and the lower Rappahannock River.*

The sum of the suggestions by the community equaled an 11-array network with 8 new arrays needed beyond available infrastructure (Figure 39). Next steps needed for refining the network design were recognized as candidate specific locations/regions for the deployments, vertical resolution at locations, seasons, and annual duration of deployments. All these elements were key to maintenance and operations schedules involved in sustaining the network.



Recommendations on sampling design for the next phase of hypoxia monitoring network development

n=11 arrays.

- Mainstem bay (3)
  - if we keep an east-west pair in the mainstem and
  - we have a reference array at another latitude
- Lower tributaries: Potomac and Rappahannock. (4)
  - 2 Potomac arrays
  - 2 Rappahannock arrays
- Mobile, targeted study arrays (4)
  - 3 new as a suite for evaluating scales of variability
  - 1 existing with MD DNR and their Fishing Bay study area

- Growing the water quality network from "Fair" to "good", addressing high frequency water quality habitat conditions with this level of investment and build out of the program.
- **Recommendation for investment to PSC is targeting support for 8 new locations for arrays.**

Figure 39. *Summary of community recommendations on establishing a hypoxia monitoring network in tidal waters of Chesapeake Bay.*

Prediction of Dissolved Oxygen Concentration in Chesapeake Bay Using Deep Learning – *Guangming Zheng (NOAA)*

Seasonal hypoxia has been a persistent threat for ecosystems and fisheries in Chesapeake Bay. Hypoxia forecasts based on coupled hydrodynamic and biogeochemical models have been used for fisheries management. Their accuracy can be potentially improved with satellite-derived water-color data which may help constrain the surface concentration of organic matter. However, because of the optical complexity, it is not straightforward to extract organic matter information from water-color data in a robust fashion.

A promising approach to address this issue is to use deep learning to build end-to-end applications. By training a deep neural network with data of all variables that could affect DO concentration in the water column, improvement of hypoxia forecast is possible. Predicting dissolved oxygen concentrations was attempted with input data that account for both physical and biogeochemical factors. The physical factors are characterized by the 3-D outputs of a hydrodynamic model, which include the current velocity, water temperature, and salinity, as well as wind velocity. The biogeochemical factors are characterized by satellite-derived spectral reflectance data. Both physical and biogeochemical data are sampled on a weekly basis up to 8 weeks before the observation date of each field measured DO, which is obtained from the CBP.

In total, 150,656 training data examples from 2002–2018 were used in this study. Data from the period of 2019–2020 was used for testing the model performance. The model architecture for the combined convolutional neural network (CNN) and long short-term memory (LSTM) model, with eight time steps, was adopted. For each time step, a set of CNNs are used to extract information from the input data. This architecture mimics the evolution process of DO in natural waters. The approach represented an innovative application of deep learning towards solving water quality problems; however, Chesapeake Bay hypoxia prediction was not robust at this time.

Workshop Findings and Recommendations

Session summaries with specific findings are provided below on the State of the Science for advances in monitoring for Chesapeake Bay SAV, water clarity, dissolved oxygen, and chlorophyll *a*. Community-based recommendations offer guidance for future direction to the monitoring programs.

Session 1. Advanced monitoring approaches to enhance tidal Chesapeake Bay habitat assessment for Submerged Aquatic Vegetation

Fixed wing aircraft-based aerial imagery has provided the CBP with consistent annual, bay-wide SAV cover survey data since 1985; roots of the program and its cover assessment protocol pre-date the formation of the CBP. Coincidentally, satellite-based imagery has slowly and steadily progressed toward more publicly available image libraries and a concomitant improvement in spatial resolution; however, resolutions of the most often available imagery (i.e., tens to hundreds of square meters) were not comparable to the standard of sub-meter resolution of the aircraft aerial imagery. More recently, high resolution satellite imagery (approximately sub-10 m^2) has been increasingly publicly available as a potential data resource. Gaps in completing the annual Chesapeake Bay SAV cover survey have occurred when weather or water conditions affected access to survey tracks, or limitations imposed for national security reasons when surveying habitat adjacent to military installations.

In 2018, high resolution satellite imagery resources were used to provide supplemental data support as a gap-filling approach for completing the bay-wide annual SAV survey. Following up on the 2018 supplemental data effort, EPA funded a pilot study with VIMS to evaluate the efficacy of providing a complete an annual SAV survey using only satellite-based imagery. Lessons learned from the pilot study were shared during this workshop and illustrated the challenges and relative ineffectiveness for immediately replacing the fixed wing aircraft-based image collection along survey lines specifically using a satellite-based data collection source with 1-meter scale resolution imagery. Inconsistency in image quality further affected the success of using satellite-derived images from the currently contracted provided for conducting the equivalent of the existing aerial fixed-wing aircraft based SAV survey. Therefore, the currently contracted imagery continues to be available but most applicable on an ad hoc rather than targeted basis. The provider mage library can still be filtered for supplemental data resources when aerial surveys experience gaps in data collection, but the current capacities of available satellite imagery are not presently a good fit for replacing the fixed-wing aircraft based aerial image data collections that provide the inputs for the annual SAV survey in Chesapeake Bay.

While available satellite resources were inconsistent for meeting the specific needs of the SAV monitoring program, other satellite-based image collection resources of nearly comparable resolution exist as featured throughout the workshop (e.g., PlanetScope SuperDove resources). Such publicly available satellite image quality and quantity are continually improving. Spectral bands that are commonly provided by remote sensing platforms (i.e., Green, Red, Near Infrared) are the most important for image classification of seagrass. Radiometrically calibrated and atmospherically corrected satellite data products are increasingly and readily available.

Challenges in image characterization associated with glint can be modeled and factored into analyses to ensure image quality in image products that are sensitive to glint.

Temporal resolution of image availability has also improved with new satellite company operational models. Historically, many satellites available for data sourcing operated with single vehicles housing sensors orbiting the earth with extended return times over the Bay. This schedule offered limited image acquisition opportunities in the Bay region. Further constraints in image collection coverage occur due to random interactions with cloud cover, inappropriate tides for optimal assessment, and periods of turbidity. Alternatively, new models of data collection involving operating constellations of small, cost-effective satellites (cubesats) with 90-minute orbits around the earth (e.g., PlanetScope SuperDove) are creating unprecedented daily to sub daily image collection of Bay habitats. SAV cover is evaluated at the pixel level of resolution (approximately 4 m^2 with PlanetScope) based on frequency of encounter from the temporally dense time series of images over an area. Temporal density coupled with such high spatial resolution provides substantial advances for creating an annual SAV assessment.

Successful proof-of-concept site-specific SAV cover assessments with new satellite image resources (e.g., PlanetScope) were shown in this workshop. A regional scale test of new satellite-based protocols for SAV cover assessment is needed, informed by the successful pilot study concepts and principles. Calibration and alignment of new AI/ML-based automated accounting approaches with historical aircraft-based aerial image-based cover assessment will be needed for historical time series continuity. AI/ML algorithms count pixels while the historical accounting approach creates beds of mixed density SAV that are summed for SAV cover accounting. In the history of the SAV monitoring program, areas of low cover (<50%) are mostly sand, but the common summation reporting unit in the SAV monitoring program remains the cumulative bed area accepting variation in cover densities within beds. Currently, pixel-based SAV cover classifications omit sand pixels from the SAV area calculations and thus underestimate cover in the traditional sense of historical assessments for Chesapeake Bay. Bed delineation rules are needed to create alignment and translation from pixel to vector based solutions for SAV area accounting.

Alternatively, advances in applying AI/ML algorithms to image interpretation and classification could reverse engineer the accounting on the historical SAV cover image library and create pixel-based accounting for the bay, recreating the full time series with an alternative method of interpreting the annual bay-wide cover accounting. The diverse and dynamic nature of Chesapeake Bay habitats has challenged algorithm development, however, advances are being made with algorithm development that demonstrate our growing capacity and opportunity to provide effective SAV cover assessments across systems with diverse habitats using satellite-based data resources (Coffer et al. 2023).

Present research has demonstrated advances in our opportunities for operationalizing a monitoring scheme with satellite-based programming 1) at potentially lower cost with freely available satellite imagery, 2) at bay-wide scale, 3) across all seasons, 4) across all salinity zones, 5) at high spatial resolution, 6) with the observational power to use daily to sub daily image collection, 7) also resolving historical aerial image data collection limitations due to national security when working around military installations, and 8) AI-based algorithms (i.e., Support

Vector and Convolutional Neural Network algorithms) are performing similarly on classification with the PlanetScope SuperDove image interpretation.

Submerged Aquatic Vegetation – Recommendations

- Continue to acquire satellite imagery to supplement the annual aerial image-based SAV cover assessment, however, focus on gap areas where restricted air-space access makes aerial image acquisition difficult.
- Scale up the local level proof-of-concept work to the regional scale with satellite-based imagery and AI/ML derived characterization of SAV cover.
- Expand temporally the proof-of-concept with regional scale SAV cover evaluation to a full SAV season assessment to demonstrate successful operation and maintenance of new protocols (e.g., a spring season mesohaline region SAV assessment).
- Develop the automation software supporting the SAV cover assessment workflow from image acquisition through AI/ML image classification to the generation of usable biogeochemical output products.
    - Included in this work would be
        - 1) the need to eliminate training on each image
        - 2) reducing misclassification of SAV cover in pixels using water quality flags for high turbidity, CDOM, or other relevant parameters, and
        - 3) applying a repeated pixel classification approach from multiple scenes to eliminate single pixel SAV classification errors.
- Tuning of the steps in the process to take imagery like PlanetScope from data acquisition through SAV cover product development are needed. This includes creating documentation of the new, frequency-of-detection-based methods of SAV cover from satellite image interpretation, addressing sparse area cover mapping, and ensuring atmospheric correction with new imagery.
- Compare product development results of applying different AI/ML approaches – e.g., Random Forest versus Convoluted Neural Network algorithms.
- Develop a method to translate pixel-based results of commercial satellite image characterization into vector-based SAV bed area delineations in order to align outputs that include bed area and bed density consistent with historical assessment methods; coincidentally, develop a rasterized version of historical aerial imagery that demonstrates to the CB management community cover alignment between satellite-based and aerial fixed-wing based SAV cover acreages could further be used to align historical and new approaches for tracking SAV cover response to management actions.
- Adding calibration and verification field sites are needed to further support the accuracy of our survey such as establishing sentinel sites. Sites should represent the diversity of key habitats to inform and benefit algorithm tuning and long-term understanding of shifts in species distributions and changes in SAV community composition.
- Work across agencies with the currently contracted satellite imagery provider to better understand the factors controlling image acquisition at needed locations and times for more effective use of satellite resources for Chesapeake Bay SAV monitoring purposes.

Session 2. Advanced monitoring approaches to enhance tidal Chesapeake Bay habitat assessment for Water Clarity and Chlorophyll *a*.

Water Clarity

Water clarity can mean something different to each person. Metrics of interest can vary depending on the research or management interest. Secchi depth, light attenuation, and turbidity are measures often used to interpret clarity, as well as component metrics of colored dissolved organic matter, chlorophyll and total suspended solids that influence observations and interpretation of clarity as highlighted in the workshop. These metrics are often assessed conditions at a point location at one moment in time. However, some measures are now observed with *in situ* fixed-location sensors that provide a high temporal density time series for a location, or use of a water quality sensor package mounted on a boat to create a transect from underway high frequency data collection with results interpolated into map coverage for an area. Research examples of satellite-based remote sensing with clarity measures over large scales in estuarine and coastal waters illustrated the potential for its use in water quality monitoring programs.

State of the science research demonstrated water clarity characterization can be evaluated over bay-wide scales using satellite-based resources with published interpretive algorithms. However, consistent monitoring of water clarity with satellite-based resources remains immature. Limitations to accuracy are presently a function of limited calibration and verification data across diverse habitats in the tidal waters of the bay. A network of calibration and verification sites is needed representing diverse habitats in Chesapeake Bay to create more robust evaluations of water clarity and reduce uncertainty in clarity classifications supporting future status and trend assessments. Tradeoffs on selecting a satellite-resource for a monitoring program basis are highlighted in the table below.

The guidance provided in the workshop suggests 1) using the best measurement for the specific research or management needs/goals, and 2) validate the measurement that is most needed.

Water clarity – Recommendations

- Sustain existing long-term water quality monitoring and shallow water monitoring program efforts that already provide the foundations for calibration and verification of satellite data products.
- Establishing a network of calibration and verification sites for K_d measures is recommended, operating during the SAV growing season at a minimum, and expanding to year-round (considering changing environmental conditions on growing season duration). Locate sites to represent diverse, shallow water habitats of the optically complex tidal waters in Chesapeake Bay to support robust calibration of satellite resources.
- Evaluate newer satellite image sources for improving water clarity assessment accuracy and spatial resolution.
- Research is needed to tune and improve existing, published algorithms for interpreting water clarity from satellite-based data or creating new algorithms that improve accuracy beyond existing algorithm characterizations of available satellite-based data resources.

Chlorophyll

Advances in remote sensing of chlorophyll continue to improve. Research shows that chlorophyll *a* condition assessment can be generated using satellite-borne sensor data and support interannual environmental change assessments at medium to high resolution at the bay-wide scale. Examples of satellite-derived time series for chlorophyll *a* condition in Chesapeake Bay have been published or are in the process of being published offering the opportunity to consider peer-reviewed approaches for adoption into monitoring program protocols for long-term habitat condition assessments. The Chesapeake Bay long-term tidal water quality monitoring program has conducted annual assessments of site-specific discrete data collections since 1985; shallow water monitoring initiated in the 2000s helped improve water quality assessments have been built upon and continue to use point data and DATAFLOW transect data for mapping chlorophyll conditions on a limited number of Chesapeake Bay management segments each year. However, advances highlighted in the workshop with satellite-based data are using government owned and operated satellites for bay-wide chlorophyll condition assessments. Data access to these satellite data are cost-free making the use of satellite-based monitoring attractive from a cost effectiveness perspective in the annual budgeting of any water quality monitoring program. Advances in Harmful Algal Bloom (HAB) species detection with satellite-based resources aligned with ground truthing efforts are evolving for Chesapeake Bay and could enhance the utility of satellite-based products for water quality assessments.

Chlorophyll a – Recommendations

- Sustaining existing long-term monitoring and shallow water monitoring program efforts is critical to continue providing robust calibration and verification of evolving satellite data products.
- Given the groundbreaking work to develop annual bay-wide chlorophyll characterization with consistent protocols across decades, support is needed for work through workshop, action team or other venue bringing researchers, analysts, and managers together to align needs and expectations for a viable bay-wide, quantitative chlorophyll criteria assessment protocol using satellite-based data resources.
- HAB characterization from satellite-based assessment is needed to translate the existing Chesapeake Bay narrative criteria that applies to waters without quantitative criteria such that narrative criteria can expand the basis of quantitative assessment support from the outputs related to HAB metrics (i.e., frequency, magnitude, duration, timing and distribution/spatial extent).
- Upon completion of protocol development for satellite-based chlorophyll a assessment, submit documentation with CBP community support for EPA approval and publication of methods to serve as reference to the management community on habitat assessment.

Session 3. Advanced monitoring approaches to enhance tidal Chesapeake Bay habitat assessment for Dissolved oxygen.

Advanced monitoring and assessment approaches are necessary to fully assess water quality standards attainment in all 92 segments of Chesapeake Bay. Dissolved oxygen criteria attainment assessment is particularly limited by a lack of high temporal frequency water quality data collection in open and deep waters to address short-duration criteria (i.e., 7-day mean, 1-day mean, instantaneous minimum). USEPA (2003) considered the long-term Chesapeake Bay water quality monitoring network as “Marginal” for assessing all scales of space and time defined by the then newly developed water quality criteria. “Recommended” levels of monitoring were envisioned as having vertical arrays or water quality profilers collecting high temporal density water quality measures for dissolved oxygen, salinity and temperature at each of the 156 long-term water quality monitoring stations (USEPA 2003).

New vertical sensor arrays that are robust, portable, and more cost-effective than previously tested designs were successfully pilot tested on the open waters of Chesapeake Bay during 2019 and 2020. The new arrays can collect the necessary high temporal frequency salinity, temperature and dissolved oxygen data from open water deployments to support habitat and criteria assessment at durations and temporal density rarely available until now. The infrastructure is designed to address a monitoring gap recognized in the CBP program since 2003 to support dissolved oxygen criteria assessment across all applicable time scales (i.e., instantaneous to 30-day mean). Dissolved oxygen criteria assessment is built around living resource needs making the data and analyses directly aligned with fish and shellfish habitat assessment needs.

Many groups are interested in improving the quality of habitat assessments and therefore the development and growth of the hypoxia monitoring network. The success of the 2019 GIT funded pilot study success initiated effective, open water column monitoring with high-temporal density. Such methods had been explored but not fully realized to gather water column habitat data at seasonal scales. Sampling design considerations were provided by workgroups with diverse interests. Results of the community survey were folded into a target number of monitoring arrays that represent the “small number” referred to by the authors of the monitoring design recommendations highlighting an ‘adequate’ (i.e., good) level of resource investment to support monitoring needs addressing short duration habitat conditions. Network development will support the fisheries, water quality monitoring and modeling communities with the new salinity, temperature and dissolved oxygen data streams.

Research on 4D habitat assessment has matured in the scientific literature since the findings of 2008 STAC panel report (Curriero et al. 2008) which indicated that techniques were not yet available to address the challenges of building and supporting a 4D water quality interpolator. A Generalized Additive Model (GAM) solution to the challenge of 4D interpolation was featured in this workshop. The pilot of a GAM 4D interpolator over a major region of the mainstem Chesapeake Bay has been successfully implemented at the scale of daily mean application. Reducing uncertainty, scaling up to bay-wide application, and integrating new high temporal density data streams, and incorporating short-term variability in dissolved oxygen measures are development steps identified for moving forward and completing the Phase 1 tool outlined in the workshop.

Dissolved oxygen - Recommendations

- A study design is needed for distribution of stations for habitat assessments that includes fixed and rotating stations in accordance with habitat assessment requirements (e.g., 3-

year assessments in each segment for dissolved oxygen criteria attainment assessment support).

- At least one vertical array should be outfitted with sensors at 1-m depth intervals to serve as a reference.
- Complete and implement use of the 4D interpolator to support DO criteria and other habitat assessments for the tidal waters of Chesapeake Bay.
- Finalize investments into completing a 10-array system of fixed and mobile stations that support bay-wide assessment through a rotating distribution of infrastructure.
- Sustain existing long-term monitoring and shallow water monitoring program efforts that provide spatial and temporal coverage in habitats to support 4D interpolator-based habitat assessment products.
- Upon completion of community supported protocol development and assessment, provide documentation for EPA approval and publication of the proposed methods to serve the community as a published reference for the methods.

Conclusion

Advanced water quality and living resource monitoring and analysis methods are actively progressing toward new or updated assessment protocol options that are suitable for CBP monitoring program adoption and operational use. Satellite-based SAV cover assessments including AI/ML based image interpretation represent the most mature method developments. Conversely, satellite-based water clarity assessments are feasible at bay-wide scales but have limitations due to a paucity of calibration and verification data. However, the workshop results show that the variation in maturity of new method applications is evolving at different paces depending on the parameter of interest.

References

Bever, A.J., M.A.M. Friedrichs, C.T. Friedrichs, and M.E. Scully. 2018. Estimating Hypoxic Volume in the Chesapeake Bay Using Two Continuously Sampled Oxygen Profiles. *Journal of Geophysical Research: Oceans* 123: 6392-6407.

Bever, A.J., M.A.M. Friedrichs, C.T. Friedrichs, M.E. Scully, and L.Q.J. Lanerolle. 2013. Combining observations and numerical model results to improve estimates of hypoxic volume within the Chesapeake Bay, USA. *Journal of Geophysical Research: Oceans* 118: 4924– 4944.

CBP 2014. Chesapeake Watershed Agreement. 23pp. Chesapeake Bay Watershed Agreement.

Cerco, C., S-C Kim, and M. Noel, 2010. The 2010 Chesapeake Bay eutrophication model. A Report to the US Environmental Protection Agency Chesapeake Bay Program and to the US Army Engineer Baltimore District. http://www.chesapeakebay.net/publication.aspx?publicationid=55318

Coffer, M.M., D.D. Graybill, P,J. Whitman, B.A. Schaeffer, W.B. Salls, R.C. Zimmerman, V. Hill, M.C. Lebrasse, J. Li, D.J. Keith, J. Kaldy, P. Colarusso, G. Raulerson, D. Ward, and W.J. Kenworthy. 2023. Providing a framework for seagrass mapping in United States coastal ecosystems using high spatial resolution satellite imagery. *Journal of Environmental Management* 337:117669.

Curriero, F., E. Hofmann, R. Murtugudde, J. Shen, and J.A. Royle. 2008. Assessing the feasibility of developing a four-dimensional (4-D) interpolator for use in impaired waters listing assessment: report of the Chesapeake Bay Program STAC Expert Panel. STAC Publication 08-008. (Available: https://www.chesapeake.org/stac/Pubs/4dreport.pdf).

He, J., G. Christakos, W. Jiaping, M. Li, and J. Leng. 2021. Spatiotemporal BME characterization and mapping of sea surface chlorophyll in Chesapeake Bay (USA) using auxiliary sea surface temperature data. *Science of the Total Environment* 794: 148670. doi: 10.1016/j.scitotenv.2021.148670.

Hernandez-Cordero, A.L., P.J. Tango, and R. Batiuk. 2020. Development of a multimetric water quality indicator for tracking progress towards the achievement of Chesapeake Bay water quality standards. *Environmental Monitoring and Assessment* 192: 94.

Hu, C., B.B. Barnes, B. Murch, and P.R. Carlson. 2014. Satellite-based Virtual Buoy System to Monitor Coastal Water Quality. Optical Engineering 53(5): 051402.

Landry, B., P. Tango, C. Bisland, M. Coffer, B. Dennison, V. Hill, C. Lebrasse, J. Li., R. Orth, C. Patrick, B. Schaeffer, P. Witman, D. Wilcox, and R. Zimmerman. 2021. Exploring Satellite Image Integration for the Chesapeake Bay SAV Monitoring Program. (Available: https://www.chesapeake.org/stac/wp-content/uploads/2021/03/FINAL-STAC-Report_Exploring-satellite-data-for-the-CB-SAV-Monitoring-Program-1.pdf).

Lebrasse, M.C., B.A. Schaeffer, M.M. Coffer, P.J. Whitman, R.C. Zimmerman, V. Hill, K.A. Islam, J. Li, and C. Osburn. 2022. Temporal stability of seagrass extent, leaf area, and carbon storage in St. Joseph Bay, Florida: a semi-automated remote sensing analysis. Estuary. Coast 45: 2082-2101.

Liang, D., J.M. Testa, L.A. Harris, and W.R. Boynton. 2022. A hydrodynamic model-based approach to assess sampling approaches for dissolved oxygen criteria in the Chesapeake Bay. *Environmental Monitoring Assessment*. 195(1): 163. doi: 10.1007/s10661-022-10725-1.

Matli, V.R.R., S. Fang, J. Guiness, N.N. Rabalais, J. K. Craig and D.R. Obenour. 2018. Space-Time Geostatistical Assessment of Hypoxia in the Northern Gulf of Mexico. *Environmental Science & Technology* 52 (21): 12484–12493. https://doi.org/10.1021/acs.est.8b03474

Matli, V.R.R., A. Laurent, K. Fennel, K. Craig, J. Krause, and D. R. Obenour. 2020. Fusion-Based Hypoxia Estimates: Combining Geostatistical and Mechanistic Models of Dissolved Oxygen Variability. *Environmental Science & Technology*. *54* (20), 13016-13025. https://doi.org/10.1021/acs.est.0c03655

MRAT. 2009. Monitoring Realignment Action Team: Final report to the Chesapeake Bay Program Management Board. October 27, 2009. Microsoft Word - MRATSynthesis27Oct09.doc

Murphy, R.R., E. Perry, J. Harcum, and J. Keisman. 2019. A Generalized Additive Model approach to evaluating water quality: Chesapeake Bay case study. *Environmental Modelling & Software*. 118: 1-13.

Obenour, D., D. Scavia, N.N. Rabalais, R.E. Turner, and A. M. Michalak. 2013. Retrospective Analysis of Midsummer Hypoxic Area and Volume in the Northern Gulf of Mexico, 1985-2011. *Environmental Science & Technology* 47(17): 9808-9815.

R Core Team (2024). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Schaeffer, B.A., P. Whitman, R. Conmy, W. Salls, M. Coffer, D. Graybill, and M.C. Lebrasse. 2022. Potential for commercial PlanetScope satellites in oil response monitoring *Marine Pollution Bulletin* 183, 114077

Testa, J.M., Y. Li, Y.J. Lee, M. Li, D.C. Brady, D.M. DiToro, W.M. Kemp, and J. Fitzpatrick. 2014. Quantifying the effects of nutrient loading on dissolved O2 cycling and hypoxia in Chesapeake Bay using a coupled hydrodynamic–biogeochemical model. Journal of Marine Systems 139:139-158.

Turner, J.S., K.A. Fall, and C.T. Friedrichs. 2023. Clarifying water clarity: A call to use metrics best suited to corresponding research and management goals in aquatic ecosystems. *Limnol. Oceanogr. Letters* 8:388-297.

U.S. Environmental Protection Agency. 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. U.S. Environmental Protection Agency, Region III, Chesapeake Bay Program Office, Annapolis, MD.

U.S. Environmental Protection Agency. 2004. Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll *a* for the Chesapeake Bay and Its Tidal Tributaries. 2004 Addendum. EPA 903-R-03-002. U.S. Environmental Protection Agency, Region III, Chesapeake Bay Program Office, Annapolis, MD.

U.S. Environmental Protection Agency. 2007. Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll *a* for the Chesapeake Bay and Its Tidal Tributaries—2007 Addendum. EPA 903-R-07-003. CBP/TRS 285- 07. U.S. Environmental Protection Agency, Region III, Chesapeake Bay Program Office, Annapolis, MD.

U.S. Environmental Protection Agency. 2008. Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll *a* for the Chesapeake Bay and Its Tidal Tributaries—2008 Technical Support for Criteria Assessment Protocols Addendum. EPA 903-R-08-001. CBP/TRS 290-08. U.S. Environmental Protection Agency, Region III, Chesapeake Bay Program Office, Annapolis, MD.

U.S. Environmental Protection Agency. 2010. Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment. U.S. Environmental Protection Agency, Region 3 Chesapeake Bay Program Office, Annapolis, MD.

U.S. Environmental Protection Agency. 2017. Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll *a* for the Chesapeake Bay and Its Tidal Tributaries. 2017 Technical Addendum. EPA 903-R-17-002. U.S. Environmental Protection Agency, Region III, Chesapeake Bay Program Office, Annapolis, MD.

Virginia Department of Environmental Quality. 2016. Critical Review of the Assessment Methodology for James River Chlorophyll- a. Virginia Department of Environmental Quality.

Virginia Department of Environmental Quality. 2019a. “Amendments to the Tidal James River Special Standard for Chlorophyll- a (Form: TH- 03).” https:// townh all. virginia. gov/L/ GetFi le. cfm? File= 103\3522\8678\ AgencyStatement_ DEQ_ 8678_ v1. pdf.

Virginia Department of Environmental Quality. 2019b. Recommended Numeric Chlorophyll- a Criteria for the James River Estuary. Virginia Department of Environmental Quality.

Wilson, D. 2019. Report to the Chesapeake Bay Trust on pilot study of offshore hypoxia monitoring. Link

Windle, A. E., H. Evers-King, B.R. Loveday, M. Ondrusek, and G.M. Silsbe, G. M. 2022. Evaluating atmospheric correction algorithms applied to OLCI Sentinel-3 data of Chesapeake Bay waters. Remote Sensing, 14(8), 1881.

Wolny A., L. Cerrone, A. Vijayan, R. Tofanelli, A.V. Barro, M. Louveaux, C. Wenzl, S. Strauss, D. Wilson-Sánchez, R. Lymbouridou, S.S. Steigleder. C. Pape, A. Bailoni, S. Duran-Nebreda, G.W. Bassel, J.U. Lohmann, M. Tsiantis, F.A. Hamprecht, K. Schneitz, A. Maizel, and A. Kreshuk. 2020. Accurate and Versatile 3D Segmentation of Plant Tissues at Cellular Resolution. *eLife* 9.

Zimmerman, R., V. Hill, J. Li, and B. Schaeffer. 2019. Quantification of blue carbon burial in seagrass ecosystems and the impact of projected climate change. Annual progress report 2. NASA Grant Cooperative Agreement No. NNX17AH01G.

Appendix A: Workshop Agendas

Chesapeake Bay Program's (CBP)
Scientific and Technical Advisory Committee (STAC)
Workshop – December 9th, 2021
Advancing Monitoring Approaches to Enhance Tidal Chesapeake Bay
Habitat Assessment Water Clarity/SAV
Workshop Webpage

Thursday, December 9th

9:00 am Introduction

- Introductions: Expertise in the room
- Explanation of Overall Advanced Monitoring Workshop Purpose and Intent — *Peter Tango (USGS)*
- Objectives of SAV Session and brief review of the FY19 STAC SAV Satellite Workshop — *Brooke Landry (MD DNR)*

9:45 am **Quantification of Blue Carbon Burial in Seagrass Ecosystems from High Resolution Commercial Imagery** — *Victoria Hill (ODU)*

10: 15 am **Automating the Quantification of Submerged Aquatic Vegetation from High Resolution Satellite Imagery** — *Dick Zimmerman (ODU)*
Review of new research at Old Dominion University (ODU) on the possibilities of mapping SAV in the Chesapeake Bay using satellite-acquired data and AI.

10:45 am **Satellite Derived Seagrass Update** — *Megan Coffer, David Graybill, Cindy Lebrasse, Wilson Salls, Peter Whitman, Blake Schaeffer, Victoria Hill, Richard Zimmerman*

11:15 am **Break**

12:15 pm **Report out on Results of STAC SAV/Satellite Workshop Tasking and Calibration Exercises; Implications and Feasibility of Moving to a Satellite-based SAV Monitoring Program** — *David Wilcox and Chris Patrick (VIMS)*
Overview of work funded following the STAC SAV Satellite Workshop and completed by VIMS. David will provide a report-out on the tasking and calibration exercise, as well as discuss potential recommendations.

1:15 pm **Session Wrap-up**

2:00 pm **Workshop Adjourns for SAV/Satellite Workshop Participants**
SAV/Satellite Steering Committee will report back at 2:30.

2:30 pm **Exploring Satellite Image Integration for the Chesapeake Bay SAV Monitoring Program Steering Committee Reconvene** — *FY19 Steering Committee*
Following full-bay tasking and the calibration exercise, the FY19 workshop Steering Committee will reconvene to review the progress made and lessons learned during the tasking and calibration exercises. VIMS' report and an addendum with more detailed instructions and final recommendations will be submitted to STAC.

4:30 pm **Adjourn**

Chesapeake Bay Program's (CBP)
Scientific and Technical Advisory Committee (STAC)
Workshop – April 22, 2022
Advancing Monitoring Approaches to Enhance Tidal Chesapeake Bay Habitat Assessment on Monitoring Water Clarity and Chlorophyll a
Virtual Meeting
Workshop webpage

Friday, April 22nd

9:00 am **Welcome, Introduction and Overview of Workshop Goals**

9:30 am **State Water Clarity Assessment Review**

- 9:30 am MD and VA Water Clarity Assessment — *Mark Trice (MD DNR), David Parrish (VIMS)*
- 9:45 am DC Water Clarity Assessment — *Nicoline Shulterbrandt (DOEE)*

9:55 am **Resources and Insights for Extending to Baywide Annual Clarity-related Analyses**

- 9:55 am Short and Long-term Station-specific Water Clarity Secchi Trends — *Rebecca Murphy (UMCES)*
- 10:15 am Remote sensing of Water Clarity in the Chesapeake Bay: Advantages and disadvantages — *Jessie Turner (UConn and VIMS)*

10:35 am **Break**

10:50 am **Resources and Insights for Extending to Baywide Annual Clarity-related Analyses (Continued)**

- 10:50 am Merging Landsat-8, Sentinel-2, and in situ data to improve coastal water clarity monitoring — *Sarah Lang (University of Rhode Island)*
- 11:10 am NOAA satellite-based Products for Chesapeake Bay Water Clarity—*Ron Vogel (NOAA Satellite Applications & Research / CoastWatch)*

11:30 am **Group Discussion**

Participants will discuss in a group what products available for decision-making they are currently utilizing. This conversation is aimed at working through the following questions:

- Are advances in water clarity monitoring suitable to adopt as an update for our programs?
- What advantages or limitations if any do you see to adapting our monitoring to use outputs of recent research to advance our assessment of water clarity in the bay?
    - Cost
    - Spatial coverage
    - Temporal frequency of location coverage
    - Image resolution
    - Habitat considerations
    - Satellite continuity and comparability
    - Policy considerations
- What monitoring efforts can we recommend enhancing calibration and accuracy of assessments with satellite-based approach.

  - Does satellite-based assessment offer an option for annual frequency baywide water clarity assessments?
- What analyses updates or changes might be necessary?

12:00 pm **Lunch**

1:00 pm **Recommendations for Satellite-based Assessment of Water Clarity**
Participants will develop draft recommendations on steps toward a satellite-based assessment of water clarity for:

- Research needs
- Monitoring needs
- Management needs
- Policy needs

1:45 pm **State Chlorophyll a Assessment Review**

- 1:45 pm MD Chlorophyll a Assessment —Slides prepared by *Matt Stover (MDE)*
- 1:55 pm VA Chlorophyll a Assessment – *Tish Robertson*
- 2:05 pm DC Chlorophyll a Assessment

2:15 pm **Resources for Chlorophyll a-related Analyses**
Discussion of He et al. (2021) study on Ches Bay CHLA assessment and management implications of the assessment.

2:15 pm **Short and long-term station-specific CHLA and Secchi trends** — *Rebecca Murphy (UMCES)*

2:35 pm **USGS satellite-based CHLA assessment for Chesapeake Bay** — *Kendull Wnuk (USGS)*

2:55 pm **NOAA satellite-based CHLA assessment for Chesapeake Bay** – *Michelle Tomlinson (NOAA)*

3:15 pm **Break**

3:25 pm **Group Discussion/Recommendations:**
This discussion is aimed at what recommendations are needed from the current assessment to expand criteria, develop new criteria, and possibly new assessment protocols.

- Are you using any of the products available for decision-making? If not, why not?
- Temperature sensitivity: Do we have the right definitions of spring and summer?

Participants will develop draft recommendations on steps toward a satellite-based assessment of Chlorophyll a for:

- Research needs
- Monitoring needs
- Management needs
- Policy needs

4:25 pm **Adjourn**

Chesapeake Bay Program's (CBP)
Scientific and Technical Advisory Committee (STAC)
Workshop – May 11, 2022
Advancing Monitoring Approaches to Enhance Tidal Chesapeake Bay
Habitat Assessment on Dissolved Oxygen Assessment
Virtual Meeting
Workshop webpage

Wednesday, May 11th

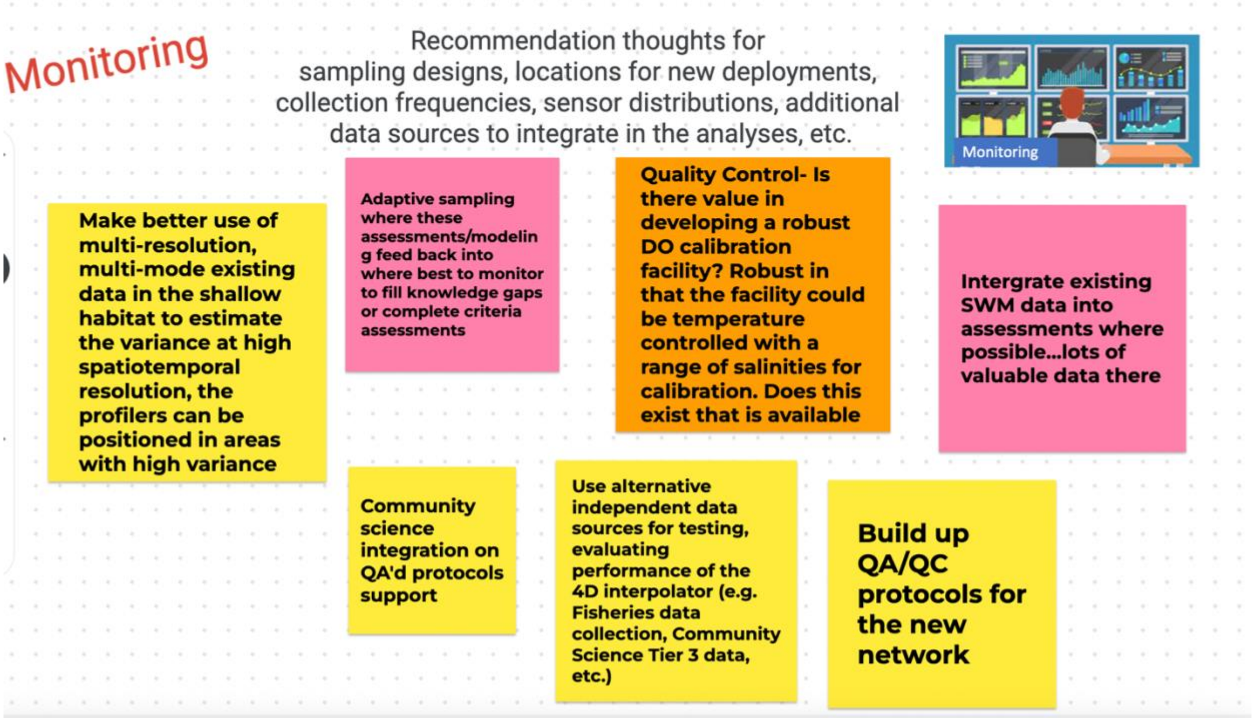
9:00 am	**Welcome, Introduction and Overview of Workshop Goals** — *Peter Tango (Chair, USGS)*
9:05 am	**Overview of Workshop Content and Goals** — *Peter Tango (USGS)*
9:30 am	**Existing Dissolved Oxygen Criteria Assessment for Chesapeake Bay** — *Richard Tian (UMCES), Qian Zhang (UMCES), Peter Tango (USGS)* The team will review the dissolved oxygen criteria assessment methods and example output.
10:00 am	**Future Criteria Assessment Protocol Framework Addressing All Time Scales of Chesapeake Bay Dissolved Oxygen Criteria** — *Gary Shenk (USGS)* Shenk will provide a framework that recognizes the new high temporal frequency dissolved oxygen data inputs of the evolving hypoxia monitoring network and the process for application to evaluate water quality criteria attainment with output from the 4-D interpolator.
10:20 am	**Options for Assessing Dissolved Oxygen Criteria** — *Dong Liang (UMCES)* Dong has been working on a spatial sampling method to improve assessment efficiency based on numerical simulations, this approach may be applicable to dissolved oxygen criteria assessment to address the full range of time duration criteria.
10:40 am	**Group Discussion** Participants will discuss preferred methods, research needs, monitoring support suggestions, management and policy requests.
11:00 am	**Break**
11:10 am	**Considerations for the Design of the 4D Water Quality Interpolator** — *Rebecca Murphy (UMCES)*
11:20 am	**Advances in development a New 4D water quality Interpolator for Chesapeake Bay** — *Elgin Perry (Statistician), Rebecca Murphy (UMCES)*
11:50 am	**Group Discussion** Participants will examine considerations regarding progress and next steps for research needs, monitoring needs, management and policy needs for adopting and implementing the 4D interpolator.
12:10 pm	**Lunch**

12:40 pm	**Investment in New Hypoxia Monitoring Network —** *Peter Tango (USGS), Bruce Vogt (NOAA), Jay Lazaar (NOAA) and Kevin Shabow (NOAA)* Hypoxia Collaborative members will speak to supporting short duration criteria assessment and discuss the two current open water stations and eight new proposed stations.
1:00 pm	**Prediction of Dissolved Oxygen Concentration in the Chesapeake Bay Using Deep Learning —** *Guangming Zheng (NOAA)*
1:30 pm	**Breakout Discussions on Monitoring, 4D and Criteria Assessment** Participants will meet in small groups to discuss workshop recommendation development on needs for research, monitoring, management and policy.
2:00 pm	**Adjourn**

Appendix B: Participants

Name	Affiliation	Name	Affiliation
Aaron Bever	Anchor QEA	Jessie Turner	UCONN
Alexander Gunnerson	CRC	Jim Hagy	EPA
Amanda Shaver	VA DEQ	Joe Wood	CBF
Andrew Keppel	MDNR	Joel Blomquist	USGS
Angie Wei	Angie Wei Consulting, Inc.	Juan Vicenty-Gonzalez	EPA
August Goldfischer	CRC	Ken Moore	VIMS
Becky Golden	MDNR	Larry Sanford	UMCES
Blake Shaeffer	EPA	Leah Ettema	EPA
Breck Sullivan	USGS	Lee McDonnell	EPA
Brooke Landy	MDNR	Lew Linker	EPA
Bruce Michael	MDNR	Lucretia Brown	DC DOEE
Bruce Vogt	NOAA	Marjy Friedrichs	VIMS
Carin Bisland	EPA	Mark Nardi	USGS
Carl Friedrichs	VIMS	Mark Trice	MDNR
Chris Patrick	VIMS	Megan Coffer	EPA
Cindy Lebrasse	EPA	Peter Tango	USGS
Cindy Johnson	VA DEQ	Peter Whitman	EPA
Claire Buchanan	ICPRB	Qian Zhang	UMCES
David Graybill	EPA	Rebecca Murphy	UMCES
David Parrish	VIMS	Renee Karrh	MDNR
David Wilcox	VIMS	Rhianne Cofer	ODU
Denice Wardrop	CRC	Richard Tian	UMCES
Diana Domotor	MDNR	Richard Zimmerman	ODU
Donald Scavia	NOAA	Ron Vogel	NOAA
Dong Liang	UMCES	Scott Phillips	USGS
Elgin Perry	Private consultant	Shelly Tomlinson	NOAA
Gary Shenk	USGS	Suzanne Brickner	NOAA
Guido Yactayo	MDNR	Tish Robertson	VA DEQ
Isabella Bertani	UMCES	Todd Lutte	EPA
Jay Lazar	NOAA	Tom Parham	MDNR
Jeremy Hanson	CRC	Victoria Hill	ODU
Jeremy Testa	UMCES	Wilson Salls	EPA

Appendix C: Jamboard Responses from Workshop Day 2, April 22, 2022, Advancing Monitoring Approaches to Enhance Tidal Chesapeake Bay Habitat Assessment on Monitoring Water Clarity and Chlorophyll a



Monitoring

Recommendation thoughts for sampling designs, locations for new deployments, collection frequencies, sensor distributions, additional data sources to integrate in the analyses, etc.

Make better use of multi-resolution, multi-mode existing data in the shallow habitat to estimate the variance at high spatiotemporal resolution, the profilers can be positioned in areas with high variance

Adaptive sampling where these assessments/modeling feed back into where best to monitor to fill knowledge gaps or complete criteria assessments

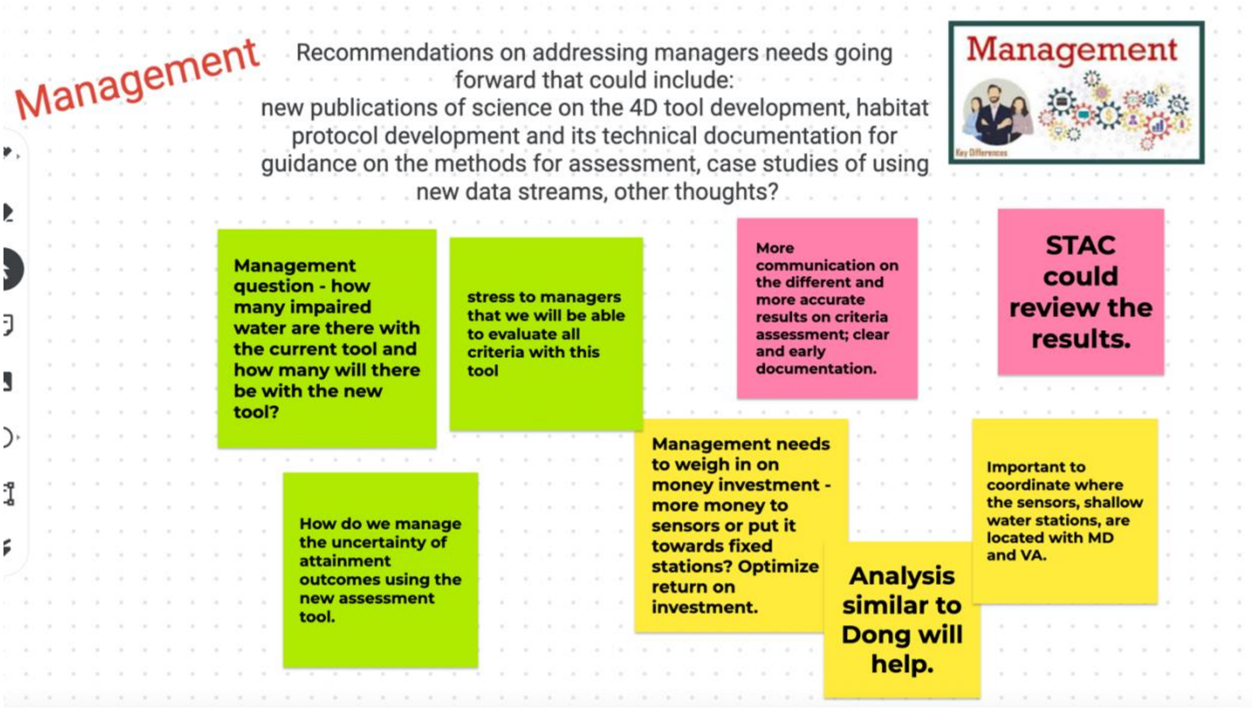
Quality Control- Is there value in developing a robust DO calibration facility? Robust in that the facility could be temperature controlled with a range of salinities for calibration. Does this exist that is available

Intergrate existing SWM data into assessments where possible...lots of valuable data there

Community science integration on QA'd protocols support

Use alternative independent data sources for testing, evaluating performance of the 4D interpolator (e.g. Fisheries data collection, Community Science Tier 3 data, etc.)

Build up QA/QC protocols for the new network



Management

Recommendations on addressing managers needs going forward that could include: new publications of science on the 4D tool development, habitat protocol development and its technical documentation for guidance on the methods for assessment, case studies of using new data streams, other thoughts?

Management question - how many impaired water are there with the current tool and how many will there be with the new tool?

stress to managers that we will be able to evaluate all criteria with this tool

More communication on the different and more accurate results on criteria assessment; clear and early documentation.

STAC could review the results.

How do we manage the uncertainty of attainment outcomes using the new assessment tool.

Management needs to weigh in on money investment - more money to sensors or put it towards fixed stations? Optimize return on investment.

Analysis similar to Dong will help.

Important to coordinate where the sensors, shallow water stations, are located with MD and VA.

Appendix D: List of Shared Resources

Day 1

- Chesapeake Monitoring Cooperative's Chesapeake Data Explorer: https://cmc.vims.edu
- FY19 STAC Workshop Report, Exploring Satellite Image Integration for the Chesapeake Bay SAV Monitoring Program, can be viewed here: https://www.chesapeake.org/stac/wp-content/uploads/2021/03/FINAL-STAC-Report_Exploring-satellite-data-for-the-CB-SAV-Monitoring-Program.pdf
- Study showing aerial derived lower density classes underestimate SAV: https://link.springer.com/article/10.2307/1353229
- https://mapseagrass.users.earthengine.app/view/seagrassmapper
- Literature on criteria via satellite for *chorophyll a* in Florida:
    - https://pubs.acs.org/doi/abs/10.1021/es2014105
    - https://www.spiedigitallibrary.org/journals/journal-of-applied-remote-sensing/volume-7/issue-1/073544/Approach-to-developing-numeric-water-quality-criteria-for-coastal-waters/10.1117/1.JRS.7.073544.full?SSO=1
- Chesapeake Dolphin Watch: https://chesapeakedolphinwatch.org/

Day 2

- Eyes on the Bay, Continuous Monitoring Station Sampling Timeline: eyesonthebay.dnr.maryland.gov/contmon/sitetimeline.cfm
- Virtual buoy system (VBS) to monitor coastal water quality: https://optics.marine.usf.edu/projects/vbs.html
- CBP DataHub: https://datahub.chesapeakebay.net/
- Tower remote sensing company, Gybe: https://www.gybe.eco/
- Marine Law Enforcement Information Network: https://news.maryland.gov/dnr/2021/01/01/tools-of-the-trade-marine-law-enforcement-information-network/
- Free NOAA Satellite Data Training Course: https://coastwatch.gitbook.io/satellite-course/lectures/introduction-to-coastwatch

Day 3

- Advancing estuarine ecological forecasts: seasonal hypoxia in Chesapeake Bay: https://esajournals.onlinelibrary.wiley.com/doi/10.1002/eap.2384
- Ambient Water Quality Criteria for Chesapeake Bay technical document series, May 2017. USEPA
- Criteria Assessment Protocol Workgroup: https://www.chesapeakebay.net/who/group/criteria_assessment_protocol_workgroup

Appendix E: List of Figures

Appendix F: List of Tables