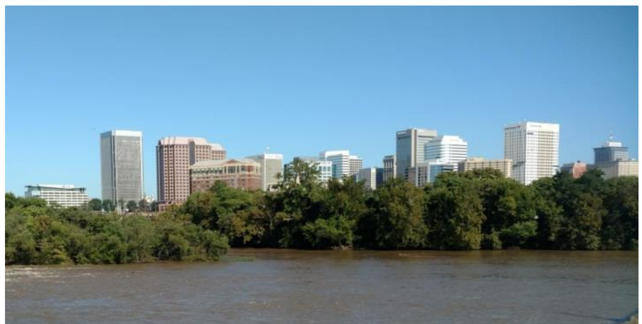
Recommended Numeric Chlorophyll-a Criteria for the James River Estuary

Virginia Department of Environmental Quality



May 13, 2019

ACKNOWLEDGMENTS

Virginia Department of Environmental Quality (VADEQ) acknowledges the contributions made by the James River Chlorophyll Study Scientific Advisory Panel (SAP), whose research provide the backbone for the recommendations presented in this document; the James River Chlorophyll Regulatory Advisory Panel (RAP) Technical Subgroup, which provided the initial review of draft versions of this document; the Chesapeake Bay Partnership Criteria Assessment Protocol Workgroup (CAP), which provided valuable feedback on the recommended assessment procedures described here; and the Chesapeake Bay Program Scientific and Technical Advisory Committee (STAC) review panel tasked with providing a very thorough peer review of previous drafts of this document. The following individuals served on these various workgroups and committees for the benefit of the James River and the Commonwealth:

Richard Batiuk, United States Environmental Protection Agency (CAP, RAP)
Clifton Bell, Brown and Caldwell (SAP, RAP)
Brian Benham, Virginia Polytechnic Institute (SAP)
Patrick Bradley, City of Richmond (RAP)
Claire Buchanan, Interstate Commission of the Potomac River Basin (SAP, CAP)
Paul Bukaveckas, Virginia Commonwealth University (SAP)
Todd Egerton, Virginia Department of Health (SAP)
Tom Fisher, University of Maryland Center for Environmental Science-Horne Point Laboratory (STAC)
Greg Garman, Virginia Institute of Marine Science (SAP)
Jim Hagy, United States Environmental Protection Agency (STAC)
Lora Harris, University of Maryland Center for Environmental Science-Chesapeake Bay Laboratory (STAC)
Will Hunley, Hampton Roads Sanitation District (SAP, CAP, RAP)
Cindy Johnson, Virginia Department of Enviromental Quality (CAP)
John Kennedy, Virginia Department of Enviromental Quality (RAP)
Mike Lane, Old Dominion University (CAP)
Dong Liang, University of Maryland Center for Environmental Science-Chesapeake Bay Laboratory (STAC)
Bruce Michael, Maryland Department of Natural Resources (CAP)
Kenneth Moore, Virginia Institute of Marine Science (SAP, CAP)
Marjorie Mulholland, Old Dominion University (SAP)
Tom Parham, Maryland Department of Natural Resources (CAP)
Dave Parrish, Virginia Institute of Marine Science (CAP)
Kimberly Reece, Virginia Institute of Marine Science (SAP)
Tish Robertson, Virginia Department of Enviromental Quality (CAP, RAP)
Oula Shehab, Dominion Power (RAP)
Matthew Stover, Maryland Department of the Environment (CAP)
Martha Sutula, Southern California Coastal Water Research Project (STAC)
Peter Tango, United States Geological Service (SAP, CAP)
Mark Trice, Maryland Department of Natural Resources (CAP)
Harry Wang, Virginia Institute of Marine Science (SAP)
Joseph Wood, Chesapeake Bay Foundation (CAP, RAP)
David Whitehurst, Virginia Department of Environmental Quality (RAP)

Lastly, much appreciation goes to Arianna Johns (VADEQ) for her invaluable technical assistance.
Cover photo credits:
Top: George Tolton (VADEQ) Middle and bottom: Tony Silvia (VADEQ)

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EXECUTIVE SUMMARY

Revisions to the numeric James River chlorophyll-a criteria, which were originally promulgated in 2005, are being proposed in light of new information produced by the James River Chlorophyll-a Study (JRCS), initiated by the Virginia Department of Environmental Quality (VADEQ) in 2011. The work produced during the JRCS focused primarily on the causes of excessive algae and the associated harmful effects of excessive algae to aquatic life in the James River estuary. The results of laboratory analyses and new monitoring data have led to a greater understanding of the issues facing the James River compared to what existed in 2005. The recommended revisions reflect this understanding.

The most salient difference between the 2005 and recommended criteria is that the latter better protect habitats as they currently exist. Monitoring of water column chlorophyll-a in the estuary has become much more sophisticated over the past ten years, and these newer, more refined datasets were used to reset each criterion to the baseline condition of their respective segment and season. These datasets were also used to characterize the spatial and temporal variability of the James River segments in the most robust manner possible, enabling the systematic selection of seasonal means that provide protection of the aquatic life designated use with respect to explicit endpoints.

Table A contrasts the 2005 criteria with the recommended values (expressed as seasonal geometric means in µg/L). Three criteria are lower than the baseline concentration for their respective segment-season due to the presence of excessive harmful algal-related effects. Table B shows the recommended short-duration criteria, which protect aquatic life specifically from toxic harmful algal blooms occurring during the summer.

Table A. Comparison of 2005 criteria and recommended criteria, both expressed as seasonal geometric means (µg/l)

Segment-Season	2005 Criteria	Recommended	Basis for recommended criteria lower than baseline
JMSTFU-spring	10	8	
JMSTFU-summer	15	21	Enhanced protection from elevated pH
JMSTFL-spring	15	10	
JMSTFL-summer	23	24	Enhanced protection from elevated pH and harmful algal blooms
JMSOH-spring	15	13	
JMSOH-summer	22	11	
JMSMH-spring	12	7	
JMSMH-summer	10	7	
JMSPH-spring	12	8	
JMSPH-summer	10	7	Enhanced protection from harmful algal blooms

Table B. Recommended short-duration chlorophyll-a (µg/l)criteria.

Segment	Spatial Application	Magnitude	Duration
JMSTFU	Lower zone of JMSTFU	52	1-month median
JMSTFL	Upper zone of JMSTFL	52	1-month median
JMSTFL	Lower zone of JMSTFL	34	1-month median
JMSOH	Entire segment	--	--
JMSMH	Entire segment	59	1-day median
JMSPH	Entire segment	20	1-day median

INTRODUCTION

Overview of the James River Estuary

The James River is one of the most iconic rivers of the United States. Affectionately known as "American's Founding River", the James brought early English settlers to Jamestown, the first permanent English settlement in the New World. The James River is not only Virginia's largest river, but it is also the largest tributary to Virginia's portion of the Chesapeake Bay and the third largest of all Bay tributaries. Approximately 3 million people live in the James River basin—about one-third of the Commonwealth's total population. Much of the population density is concentrated below the fall line, along the 110-mile stretch known as the James River estuary (commonly referred to as the Lower James). This stretch begins at Richmond and then flows in a southeasterly direction past the Presquille Wildlife Refuge, the city of Hopewell, Jamestown, and Hampton Roads until it reaches the Chesapeake Bay. As shown in Figure 1, the estuary is subdivided into five segments—the boundaries of which are based on geomorphology and salinity: upper tidal fresh (JMSTFU), lower tidal fresh (JMSTFL), oligohaline (JMSOH), mesohaline (JMSMH), and polyhaline (JMSPH). The James River estuary is characterized by enormous productivity and biodiversity, providing habitat to key species of fish and wildlife. But like the rest of the Chesapeake Bay, water quality has declined in the James River estuary since the 1960s. Expanding agricultural, municipal, and industrial sectors have led to increases in nitrogen, phosphorous, and sediment loads into the estuary. These changes in water quality have occurred against a backdrop of disappearing submerged aquatic vegetation beds (Moore et al., 1999), declines in the abundance of commercially and recreationally important species such as the American shad (Weaver et al., 2003), degraded benthic assemblages (Diaz, 1989), and documentation of harmful algae blooms (HAB) (Marshall and Egerton, 2012) coinciding with increasing abundance of HAB-forming species (Dauer et al., 2016). In the most recent national estuaries assessment (Bricker et al. 2007), the eutrophic condition in the James River estuary was rated as "medium high",

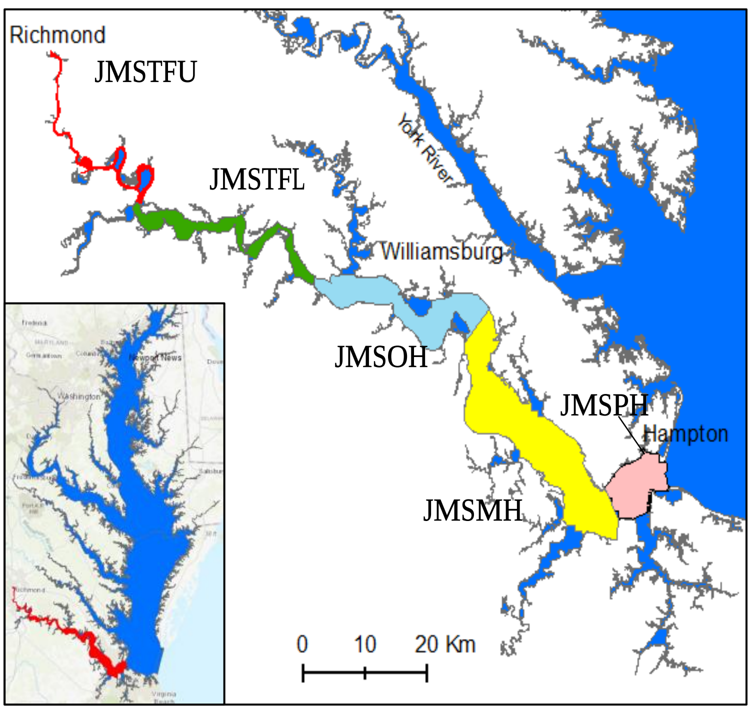


Figure 1. Map of the James River Estuary

considerably worse than the "low" rating it earned just five years prior. In 1999, the United States Environmental Protection Agency (EPA) added the mainstem tidal James River to the 303(d) Impaired Waters List due to excessive nutrients.

Scientific Basis of the 2005 Chlorophyll-a Criteria

Persistent hypoxia is found in most tributaries of the Chesapeake Bay (Bricker et al., 2007), but not in the tidal James River. The waters of the James are relatively well-mixed due to the river's shallow depth and its proximity to the Atlantic Ocean. While the absence of hypoxia is a positive trait from the aquatic life stand-point, it means that dissolved oxygen in the James may not be a reliable response variable of nutrient pollution as it is in other Chesapeake Bay sub-estuaries. In 2005, Virginia adopted numeric chlorophyll-a criteria for the tidal James River to facilitate the restoration of the aquatic life designated use with respect to nutrients (see Table 1). The implicit basis of the 2005 criteria was protection of "fish food." The criteria were derived to protect balanced aquatic plant life populations and to protect against the overgrowth of nuisance, potentially harmful algal species (VADEQ, 2005a). Due to the limitations of the James River-specific datasets at that time, inferences about what constitutes "balanced and non-nuisance" aquatic plant communities had to be made using reference datasets generated in other estuaries. Thus, the 2005 criteria assume that the James is similar to these estuaries with the exception of having higher nutrient loads. In addition to being based on chlorophyll-a concentrations associated with "healthy" phytoplankton communities, the 2005 criteria also reflect the attainable concentrations predicted by the Chesapeake Bay Water Quality Model (VADEQ, 2005b).

Table 1. The James River chlorophyll-a criteria (μg/L) adopted in 2005.

Segment	Spring (March-May)	Summer (July-September)
JMSTFU	10	15
JMSTFL	15	23
JMSOH	15	22
JMSMH	12	10
JMSPH	12	10

The James River Chlorophyll-a Study

The scientific basis for the 2005 criteria was questioned once it became apparent that the nutrient cap load set by the Chesapeake Bay Total Maximum Daily Load for chlorophyll-a criteria attainment in the James River basin (USEPA, 2010c; Appendix O) was much lower than an earlier estimate (USEPA, 2003b). Consequently, EPA tacitly agreed with the Commonwealth that there is value in reviewing the scientific bases for the chlorophyll-a standard. The James River Chlorophyll-a Study (JRCS) was initiated in 2011. The Virginia Department of Environmental Quality (VADEQ) assembled the JRCS Scientific Advisory Panel (SAP), a group of academic, federal/state, and industry scientists covering different areas of expertise related to estuarine eutrophication. The panel was charged with re-establishing the scientific basis for chlorophyll-a criteria in the James, evaluating the protectiveness of the 2005 criteria, and recommending alternative criteria, if deemed necessary. Field, laboratory, and literature research were conducted to address these questions. The JRCS-SAP issued their findings to VADEQ in 2016 (JRCS-SAP, 2016). VADEQ surmised the following key points from the JRCS-SAP report:

1. Empirical relationships between chlorophyll-a and response variables such as water clarity, pH, harmful algae bloom species abundance/toxicity, and dissolved oxygen may be evident in James River datasets.
2. These responses ("effects") make for more defensible endpoints than reference phytoplankton community metrics (diversity, evenness, richness) since the former's connection to aquatic life harm is more readily apparent.
3. The derivation of truly site-specific criteria is feasible given the available monitoring datasets.
4. The protectiveness of the 2005 criteria is highly dependent on how they are applied. There is strong evidence that the criteria are not protective if they are applied as geometric means as opposed to arithmetic means. This is a troubling finding since there is evidence that the former is more appropriate for characterizing central tendency of James River chlorophyll-a than the latter (USEPA, 2010a). The 2005 criteria were derived as arithmetic means (VADEQ, 2005a), but later re-interpreted as geometric means.

In light of the JRCS-SAP's findings, VADEQ determined there is sufficient reason to re-derive the James River chlorophyll-a criteria.

The methodology used for implementing the 2005 criteria in the context of designated use assessment was also scrutinized during the study, as presented in VADEQ (2016b). The 2006 methodology was developed independent of the criteria, which is rather unorthodox for chlorophyll-a assessment procedures. The same procedure and decision rules used for assessing Chesapeake Bay dissolved oxygen criteria—which have "hard" endpoints such as survivorship and growth—were used for the relatively "softer" James River chlorophyll-a criteria. VADEQ decided to develop an alternative assessment framework that is more forgiving of brief high exposure events given that 1) chlorophyll-a is only an indicator of potential ecological stress, not a direct cause (unlike low dissolved oxygen concentration) and 2) chlorophyll-a can be quite variable even in "healthy" mesotrophic systems (Knox, 2012). Additionally, VADEQ believes that having an approach that is built on site-specific knowledge would allow attainment determinations to be made with more confidence compared to what is possible with the current methodology. The recommended assessment approach is discussed later in this document.

CRITERIA DEVELOPMENT

Background

Water column chlorophyll-a, as a surrogate parameter of phytoplankton biomass, is positively correlated with algal primary production—which is dependent on light and nutrient availability. Thus, algal blooms driven by excessive nutrient loads will be generally reflected by elevated chlorophyll-a concentrations. In addition to fostering dramatic lulls in dissolved oxygen, algal blooms can cause elevated pH, which can exacerbate ammonia toxicity (USEPA, 2013), enhance the bioavailability of sediment-bound phosphorus (Seitzinger et al., 1991), and limit growth, reproduction, and survival of sensitive species (Locke, 1998 and references therein). Algal blooms can also contribute to poor water clarity, impeding the successful growth of submerged aquatic vegetation (Dennison et al., 1993). Furthermore, some phytoplankton species—those associated with harmful algal blooms (HABs)—can be toxic to consumers—negatively affecting the growth, reproduction, and survival of aquatic life (Lopez et al., 2008). Numeric chlorophyll-a criteria that are derived to minimize these ecological effects should provide optimal protection of the aquatic life designated use. But the derivation of numeric chlorophyll-a criteria is complicated by several issues.

First, the empirical linkage of chlorophyll-a to ecological effects is highly variable from site to site, particularly in the context of estuaries due to the presence of a salinity gradient. Both algal metabolism and salinity affect the physicochemical properties of water. For example, saline waters (meso- and polyhaline) have a higher buffering capacity than less saline waters (tidal fresh and oligohaline), and thus the relationship between phytoplankton photosynthesis and pH generally weakens as one moves down the estuary. Aquatic life are also adapted to the vagaries of specific salinity regimes, which means their habitat requirements vary throughout the estuary. For instance, the SAV taxa inhabiting the upper and middle reaches are adapted to relatively turbid waters and thus have less stringent light requirements compared to species inhabiting the lower reaches (Batiuk et al., 2000). Because species do not all possess the same suite of adaptations to all habitat conditions, species composition does not stay constant along the estuarine continuum. For instance, HAB-forming species inhabiting the tidal fresh (e.g., the cyanobacteria *Microcystis aeruginosa*) are of very little importance in the meso- and polyhaline segments— which support their own HAB-forming species (e.g., the dinoflagellate *Cochlodinium polykrikoides*). This means that the relationship between chlorophyll-a and HAB risk is not uniform throughout the estuary. The James River chlorophyll-a criteria (JRCC) are site-specific to mainly account for the confounding effect of salinity on relationships between algae and ecological impacts. But there are other factors—like segment area and geomorphology—that also dictate a tailored approach.

The second challenge to deriving numeric chlorophyll-a criteria stems from the fact that the effects mediated or caused by algae vary seasonally. For instance, algal-related hypoxia typically occurs when waters become stratified—a condition that rarely happens outside of the summer months in the tributaries of the Chesapeake Bay. Toxic HABs mostly occur in the warm weather months as well. Thus, protecting water clarity and pH may be the only concerns in the non-summer months, while the prevention of hypoxia and HABs will be additional concerns for the summer. To account for temporal dynamics, James River chlorophyll-a criteria are seasonal-specific: spring (March 1 to May 30) and summer (July 1 to September 30).

The diversity of ecological impacts related to algae also complicates the derivation of chlorophyll-a criteria. The changes that algae impart on a system do not all occur on the same time scales. For instance, algal photosynthesis can drive up pH levels in a matter of hours and can thus be modeled using instantaneous measurements over a relatively short period of time. But depressed DO typically occurs after an algal bloom has crashed and the waterbody is poorly mixed. This means the relationship between chlorophyll-a and hypoxia will only be evident when evaluating data that are aggregated over longer periods of time (like a season), thereby requiring many years' worth of monitoring data. Additionally, the diverse forms of aquatic life in the Bay and its tidal tributaries have different tolerances to different effects. Most estuarine organisms are not severely stressed by sporadic incidents of slightly elevated pH in the absence of other stressors (but see the comprehensive review by Locke, 1998). In contrast, *Cochlodinium* blooms can cause extensive mortality after a single 96-hr exposure (Reece and Vogelbein, 2015). SAV coverage at a site reflects the average condition at that site over the course of the growing season, thus making it appropriate to study the relationship of water clarity parameters (e.g., total suspended solids and chlorophyll-a) averaged over the spring and summer. It is also acceptable to spatially aggregate water clarity data given how both SAV and water clarity acreage goals are currently assessed (USEPA, 2008). But similar averaging of toxic HAB data would not be appropriate. Toxic HAB events occurring 50% of the time in 50% of the habitat would not be conducive for a healthy aquatic life community. Thus, it is crucial that each algal-related effect be evaluated on the appropriate temporal and spatial scale when deriving criteria.

Lastly, uncertainty vexes all water quality criteria, but especially ones adopted to prevent many effects. Chlorophyll-a criteria should not only protect against known causes of harm, but ideally they should also mitigate the effects of unidentified nutrient-related stressors, synergistic interactions of known stressors[1], and stressors that are yet to arrive (like newly documented HAB species). While physicochemical interactions are fairly predictable, biological ones are not. A waterbody could have no documented sighting of a HAB species based on 20 years of monitoring, and suddenly break that record once an exotic species establishes a foothold—

[1] Dow and Swoboda (2000) provide an example of a synergistic interaction of algal-related stressors. Ammonia released from decomposing cyanobacteria can cause fish gill damage when algal photosynthesis drives pH to high levels. Fish gill damage can enhance microcystin uptake, thus leading to liver necrosis.

perhaps one mediated by natural or anthropogenic disturbances to the system. While it is impossible to protect aquatic life from all potentialities, it is possible to hedge against some unknowns by simply maintaining current conditions. Maintaining current conditions in waters with no known algae-related problems has the added advantage of protecting waters (both upstream and downstream[2]) where algal-related impacts have been empirically observed. But developing criteria that protect against potentially deleterious shifts to the system requires a good understanding of the baseline condition. Fortunately, an enormous body of monitoring data is available for the James River estuary to establish the baseline. These data not only span a wide temporal breadth, but in more recent years, monitoring efforts have also generated a wealth of spatially-intensive datasets.

Conceptual Framework

Chlorophyll-a criteria that provide protection against harmful effects can be contrasted with criteria derived to mirror chlorophyll-a concentrations associated with reference phytoplankton communities. The JRCS-SAP weighed the merits and downsides to both types of criteria (JRCS-SAP, 2016; Buchanan, 2016). While VADEQ acknowledges that reference-based criteria have the advantage of being more protective than effects-based criteria, the agency believes that it is important for criteria to be established on the basis of harmful effects, since the goal to minimize harmful effects is easily appreciated by both resource managers and stakeholders. Additionally, the science and technical guidance is much more developed for effects-based criteria (see EPA, 2010b). Technical defensibility has special importance to VADEQ given the questions raised over the 2005 criteria.

The derivation approach (illustrated in Figure 2) begins by defining the typical chlorophyll-a expression for each segment-season. This "baseline" is estimated through the analysis of recent monitoring datasets and not only involves a calculation of normal chlorophyll-a central tendency, but also the normal spatial and temporal variability of chlorophyll-a. Then, empirical relationships (models) connecting chlorophyll-a to various response variables are used to predict whether harmful effects are expected to occur during a season with typical chlorophyll-a expression. If a specific harmful effect takes months to manifest, then the pertinent empirical model is used to find the highest seasonal central tendency expected to incur minimal effect. If a harmful effect occurs rapidly (over hours), its pertinent empirical model is used to predict the chlorophyll-a concentration associated with the harmful effect (the "effect threshold") and then a probability model is used to determine the likelihood of exceeding the effect threshold given baseline chlorophyll-a variability and central tendency. If the baseline

[2] Pursuant to sections 303 and 101(a) of the Clean Water Act, the federal regulation 40 C.F.R. §131.10(b) requires that "In designating uses of a water body and the appropriate criteria for those uses, the State shall take into consideration the water quality standards of downstream waters and shall ensure that its water quality standards provide for the attainment and maintenance of the water quality standards of downstream waters." States/Tribes are required to protect both upstream and downstream waters in estuaries due to the bi-directional flow of these systems.

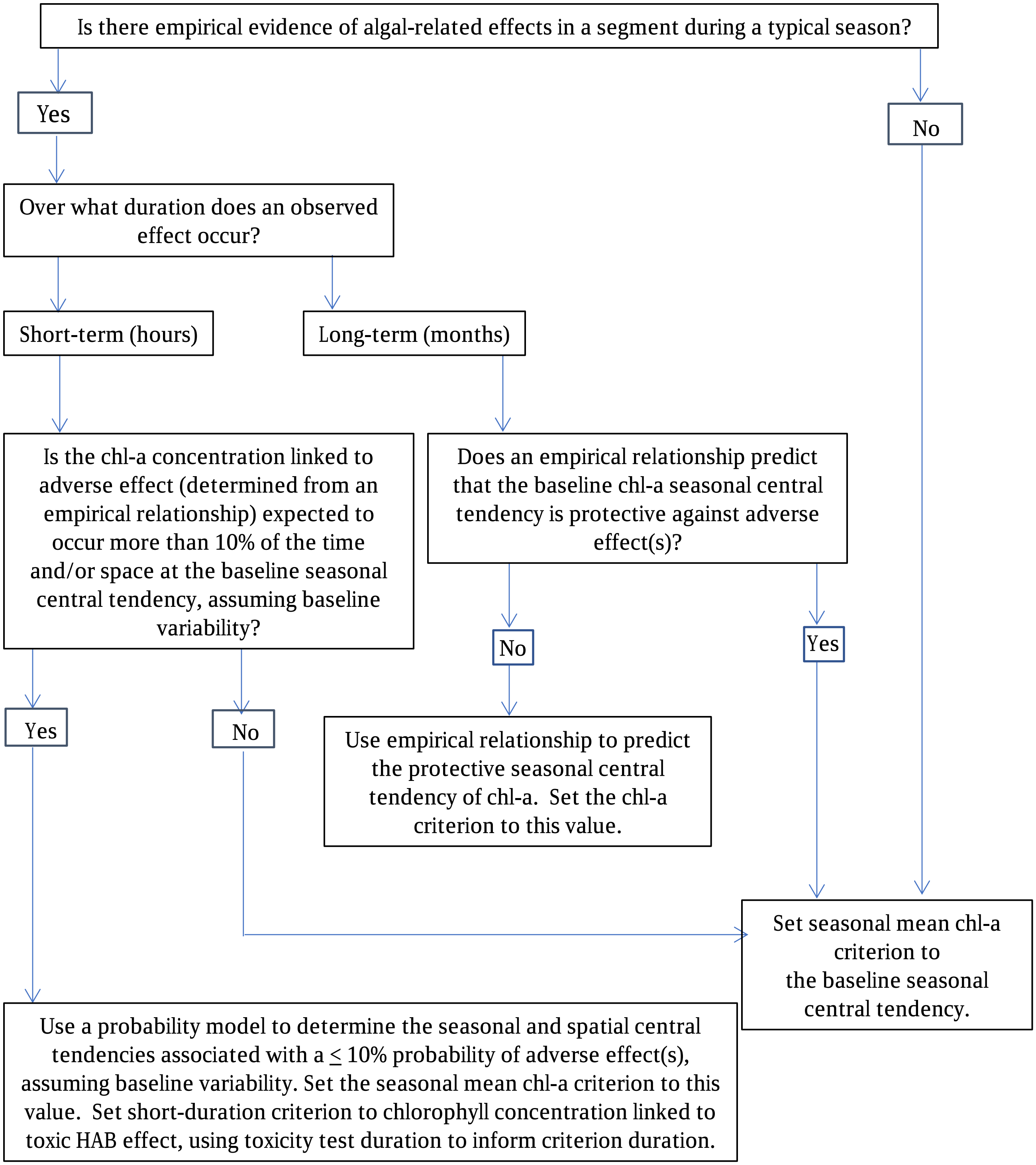


Figure 2. Conceptual diagram of VADEQ's chlorophyll-a criteria derivation approach. This diagram shares some of the same elements as the flow diagram featured in Hagy et al. (2008)

central tendency is considered unprotective of the harmful effect, the probability model is used to predict the highest central tendency conferring an acceptable risk of the harmful effect. The seasonal central tendency that protects against all observed harmful effects is then selected as the criterion. For segment-seasons where no harmful effects are expected to occur in a "typical" season, the baseline central tendency is established as the candidate criterion.

Seasonal mean criteria are paired with short-duration criteria (to not be exceeded more than 10% of the time) in those segments where an empirical relationship can be established between a toxic HAB and chlorophyll-a concentration. The magnitude of these short-duration criteria correspond to ambient chlorophyll-a concentrations that are linked to specific HAB effect thresholds, as determined from the pertinent empirical model. The duration of these short-duration criteria correspond roughly to the period of time the effect is conservatively expected to occur. Although the seasonal mean criteria are developed to protect against long-term and short-term effects, potentially damaging algal blooms could occur at a high frequency without a concomitant seasonal mean exceedance. This possibility is significantly reduced by coupling the seasonal mean criteria with short-duration criteria.

Prediction uncertainty in stressor-response curves, natural variability, and the resiliency of aquatic life to algal-related stressors dictate that effects-based chlorophyll-a criteria be developed with some degree of "allowable" risk. An overall risk level up to 10% was deemed acceptable for short-term effects—like HABs and elevated pH. This is consistent with the USEPA (2003a) recommendation that waterbodies be allowed to exceed aquatic life criteria/thresholds no more than 10% of the time. It was also deemed acceptable if, at any given time, up to 10% of the overall habitat is at high risk of impacts due to excessive algae. This is consistent with the long-standing practice of setting toxics criteria/thresholds to the pollutant concentration that is safe for at least 90% of the target population (USEPA, 2000).

Datasets

The James River chlorophyll-a criteria were re-derived using a variety of datasets (summarized in Table 2.)

Fixed station datasets

For over thirty years, each James River segment has been monitored at two or three stations[3] (see Figure 3) on a semi-monthly or monthly basis. Full dissolved oxygen vertical profiles are taken at each sampling event, along with surface chlorophyll-a samples. Datasets from 1991 to 2015 were used to determine the relationship of chlorophyll-a to dissolved oxygen in the James River. Additionally, from the years 1993 to 2010, monthly optical measurements were taken at

[3] The data collection at these stations is supported by the EPA-Chesapeake Bay Program Office. All datasets are available for download at www.chesapeakebay.net, where field and laboratory methods are also described.

each station to quantify light transparency. These measurements were combined with surface chlorophyll-a, salinity, turbidity, and total suspended solid concentrations to determine the relationship of chlorophyll-a to water clarity.

During the James River Chlorophyll-a Study (2011-2013), enhanced monitoring was conducted at the fixed stations in the tidal fresh segments. In addition to routine monthly site visits performed by VADEQ, Virginia Commonwealth University conducted surface sampling of water column chlorophyll-a, *Microcystis aeurogenosa* cell density, and extracellular microcystin concentration on a weekly basis.

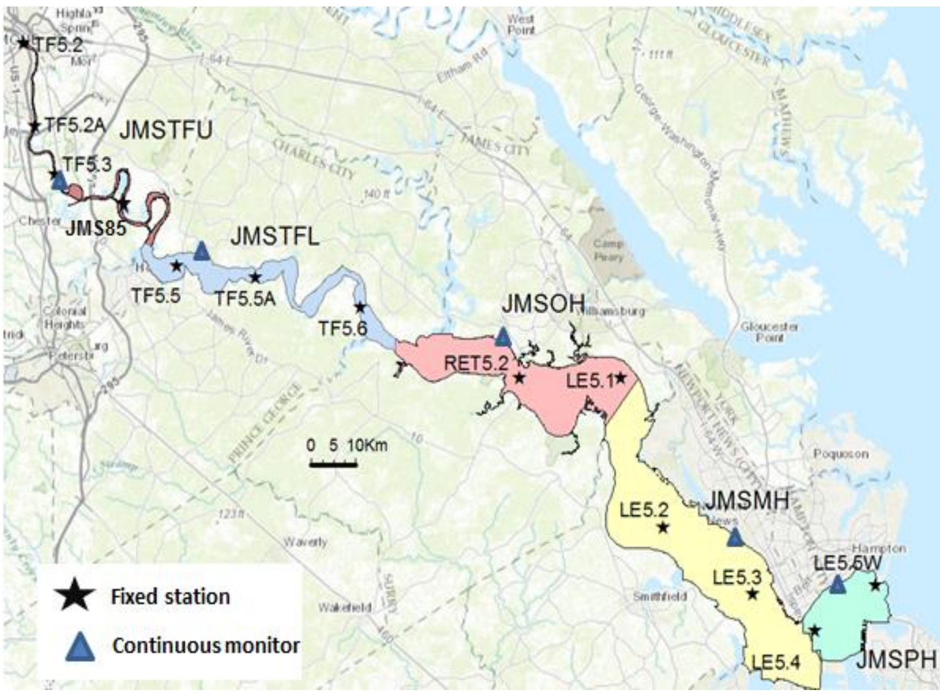


Figure 3. James River fixed stations and continuous monitor deployment sites.

Finally, for JMSTFU, JMSTFL, and JMSOH, many of the fixed station datasets from 2005-2011 were used to establish baseline seasonal chlorophyll-a means.

Continuous monitoring datasets

During the spring and summer months of 2006 to 2008, the Virginia Institute of Marine Science (VIMS) deployed continuous monitors[4] in each James River segment. These monitors (deployed at the locations indicated by the triangles in Figure 3) recorded observations of a suite of field parameters at 15-minute intervals. The sondes were also equipped with a fluorescence sensor,

[4] These monitors were deployed and maintained by the Virginia Institute of Marine Science (VIMS). Information about these datasets can be found at www.vecos.org, where they can also be downloaded.

thereby enabling the estimation of water column chlorophyll-a concentration. These datasets were used to relate chlorophyll-a to pH since discrete samples (which tend to be collected in the morning or early afternoon) rarely capture the high pH values that continuous monitors observe over the diel cycle.

Continuous datasets were also used to calculate the baseline temporal variance for JMSTFU, JMSTFL, and JMSOH.

Dataflow datasets

Starting in 2005, VIMS and Hampton Roads Sanitation District (HRSD) began conducting spatially-intensive water quality monitoring in the James. The "Dataflow" system[5], in which a sonde housed in a flow-through chamber is attached to the back of a vessel, permits underway observations of multiple field parameters, including chlorophyll-a concentration translated from fluorescence. These observations (illustrated in Figure 4) can then be used to create high-resolution two-dimensional maps of water quality. This makes Dataflow datasets superior to fixed station datasets at characterizing chlorophyll-a spatial distribution. These datasets were relied on for establishing both baseline central tendencies and spatial variation. Because HRSD conducted weekly Dataflow monitoring runs in JMSMH and JMSPH, the datasets can be considered "high-frequency" as well as "spatially-intensive"; thus, they were also used to estimate baseline temporal variances in these segments. Additionally, phytoplankton sampling conducted in concert with Dataflow cruises enabled ambient chlorophyll-a concentrations to be related to harmful algae bloom events.

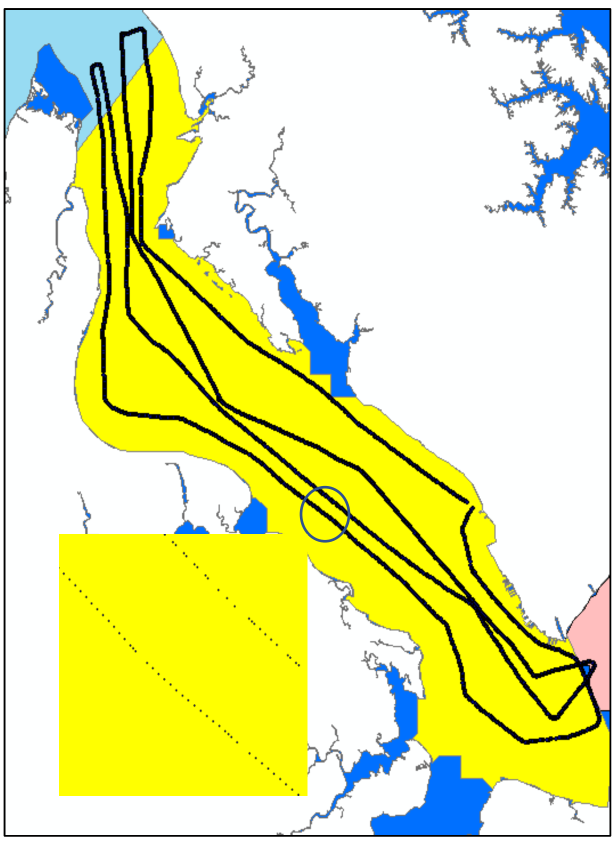


Figure 4. The JMSMH Dataflow cruisetrack, in which observations (represented here as points) are taken approximately every 60-80 meters.

Laboratory datasets

HAB bioassays were conducted by VCU and VIMS, and these datasets were used by the JRCS-SAP to develop effect thresholds for harmful phytoplankton. The effects of the cyanobacteria *Microcystis aeruginosa* and its associated toxin microcystin were studied by

[5] The Dataflow monitoring system is used by VIMS and the Hampton Roads Sanitation District (HRSD) to create two-dimensional maps of water clarity and chlorophyll-a. Information about these datasets can be found at www.vecos.org, where they can also be downloaded.

VCU and VIMS in relation to clam filtering rate and fish grazing rates (Bukaveckas et al., 2014; Wood et al., 2016), fish survivorship (Vogelbein and Reece, 2013; Bukaveckas et al., 2014), cladoceran survivorship (Vogelbein and Reece, 2013; Bukaveckas et al., 2014), and zooplankton feeding and reproduction (Bukaveckas et al., 2014). The toxicity of a number of toxic diatom and dinoflagellate species were studied by VIMS in relation to oyster veliger, brine shrimp, and fish survivorship (Vogelbein and Reece, 2013; Reece and Vogelbein, 2015). Of these taxa, *Cochlodinium polykrikoides* was identified as the most abundant and thus poses the most persistent threat to James River aquatic life. The results of *C. polykrikoides* toxicity tests were evaluated alongside others published in the literature (see sources within JRCS-SAP, 2016).

Table 2. Summary of datasets used for the re-derivation of James River chlorophyll-a

Dataset	Time period	Used to estimate, model, or develop...	Source
Fixed Station	2009-2015 1986-2015 1993-2010 2011-2013	Baseline seasonal central tendencies (tidal fresh and JMSOH) Relationship of chl-a and DO Relationshp of chl-a and water clarity Relationship of chl-a and Microcystis/microcystin (tidal fresh)	CBPO/VADEQ, VCU
Continuous	2006-2008, 2012-2015	Estimate baseline temporal variance Model relationship of chl-a and pH	VIMS, HRSD
Dataflow	2005-2015 2005-2015 2005-2015 2011-2014	Baseline seasonal central tendencies Baseline spatial variance Baseline temporal variance (JMSMH and JMSPH) Relationship of chl-a and Cochlodinium density (JMSMH and JMSPH)	VIMS,HRSD
Laboratory	2011-2014	Microcystis/microcystin effect threshold Cochlodinium density effect threshold	VCU, VIMS, literature

Effect Thresholds

Thresholds (summarized in Table 3) were identified for all the "effect" variables recommended by the JRCS-SAP. Values at or above these thresholds are expected to harm aquatic life. Using a combination of laboratory and published results, the JRSCS-SAP recommended two thresholds for James River HABs: 1) a microcystin concentration of 0.8 µg/L (based on reduced grazing rates of the wedge clam *Rangia cuneata)* and 2) a *Cochlodinium polykrikoides* cell density of 1,000 cells/ml (based on 20% mortality of multiple test subjects). In regards to the former, VADEQ believes that a threshold of 1 µg/L would be more defensible based on current scientific knowledge since it corresponds to the value recommended by the World Health Organization for drinking water protection (Chorus and Bartram, 1999).

For the physicochemical variables, the effect thresholds are codified in Virginia's Water Quality Standards (VSWCB, 2017). For pH, the tidal James River is not supposed to exceed a pH of 9.0. Thus, 9.1 was used as an effect threshold for pH. For DO, the 30-day average concentration is not supposed to fall below a 30-day DO mean of 5.5 or 5.0 mg/L (depending on salinity), so these values were used to identify waters at risk for chronic hypoxia. For water clarity, shallow tidal fresh and oligohaline waters must maintain an average percent-light-through-water (PLW) of 13% throughout the SAV growing season, while more saline waters must maintain a PLW of 22%. These PLW thresholds are recommended by Batiuk et al. (2000).

Table 3. Effect Thresholds

Effect variable	Threshold	Duration	Primary Source
Microcystin concentration	>1 µg/l	4-8 weeks	JRCS-SAP (2016) Chorus and Bartram (1999)
C. polykrikoides cell density	>=1,000 cells/ml	96-hour	JRCS-SAP (2016)
pH	>=9.1	Instantaneous	VSWCB, 2017
Dissolved oxygen concentration	<5.0 or <5.5 mg/l	30-Day	EPA (2003)
Water clarity	<13% or <22% PLW	Growing season	Batiuk et al.(2000)

Data Analysis

Baseline Characterization

The period from 2005 to 2015 was chosen as the "baseline period"—the period over which the "typical" chlorophyll-a central tendency and spatiotemporal variance for each segment was established. This interval was chosen because it corresponds to a period of spatially and temporally-intensive water quality monitoring in the James.

Seasonal Central Tendency Estimation

At a minimum, the revised JRCC are designed to protect current (baseline) conditions as characterized by water quality data gathered in the spring (March-May) and summer (July-September) 2005 to 2015. Protection of current resources prevents degradation of upstream and downstream waters and lessens the likelihood of unidentified algal-related effects developing or growing more intense. For the tidal fresh (JMSTFU and JMSTFL) and oligohaline (JMSOH) segments, discrete samples taken at fixed stations and monthly Dataflow datasets were used jointly to establish current chlorophyll-a concentrations. Dataflow cruises were only conducted for a few years in these segments. In contrast, weekly spring and summer Dataflow cruises have been conducted every year since 2005 in the mesohaline (JMSMH) and polyhaline (JMSPH) segments. Thus, there is much less year-to-year variation in JMSMH and JMSPH seasonal estimates compared to the other segments. The upper 99% confidence limit was chosen to represent the baseline chlorophyll-a concentrations for JMSTFU, JMSTFL, and JMSOH to account for the greater measurement uncertainty for these segments, while a more restrictive statistic—the upper 95% confidence limit of the arithmetic mean of season-year estimates—was used to represent the baseline chlorophyll-a concentrations for JMSMH and JMSPH[6]. As will be described later, downward adjustments were made to the baseline central tendencies (summarized in Table 5) whenever they were determined to provide inadequate protection of algal-related effects.

For JMSOH, JMSMH, and JMSPH, the estimation of baseline central tendencies is straightforward:

1. The median of chlorophyll-a samples for each monitoring run was calculated for each segment.
2. The month-year median of monitoring run medians was calculated for each segment.
3. The season-year geometric mean of month-year medians was calculated for each segment.
4. The upper 95% (JMSMH and JMSPH) or 99% (JMSOH) confidence limit of the arithmetic[7] mean of seasonal geometric means was calculated. This is the baseline seasonal central tendency for the segment.

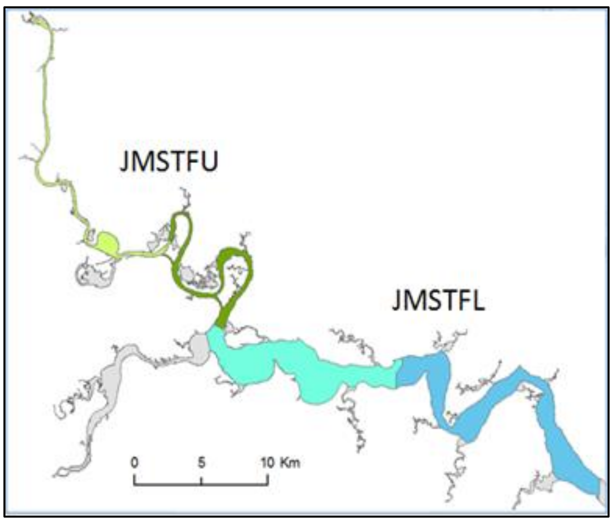


Figure 5. The "zones" of JMSTFU and JMSTFL. (Further description is provided in Appendix A).

During the James River Chlorophyll-a Study, VADEQ determined that chlorophyll-a is consistently non-uniform in both JMSTFU and JMSTFL (see Appendix A and Figure 5). In JMSTFU, analysis of mapped chlorophyll-a reveals the presence of two distinct "zones" which meet at river mile 95. The upstream "zone" has very low chlorophyll-a concentrations compared to the downstream "zone". Chlorophyll-a in the downstream zone tends to be similar to the concentrations in the upper portion of JMSTFL (represented by TF5.5 and TF5.5A)[8]. This relatively broad, shallow stretch of the estuary is where chlorophyll-a

[6] These upper confidence limits were selected on the basis of convention more than anything else. A "normal value" is conventionally defined as a value that is within two standard deviations of the population mean—which translates into 95% of the entire population being evaluated as "normal". However, the basic assumption is that all values are generated the same way and have the same measurement error. Thus, given that different data sources (using different sampling frequencies) were used to inform JMSTFU, JMSTFL, and JMSOH seasonal mean estimates, "normal" was defined in a broader-than-usual sense—any value within approximately 2.5 standard deviations of the mean.

[7] An arithmetic mean was chosen based on the assumption that interannual geometric means, like most things in nature, fall symmetrically around a central tendency.

[8] Because chlorophyll-a concentrations are similar in the lower JMSTFU and upper JMSTFL, other water quality parameters (DO, water clarity, pH, etc.) are assumed to follow a similar pattern for the purposes of re-deriving the JRCC.

reaches its maximum concentration. The downstream zone of JMSTFL, beginning at river mile 67 where the channel deepens considerably, tends to have relatively low levels of chlorophyll-a compared to the upstream portion of the segment.

Baseline central tendencies were calculated in JMSTFU and JMSTFL as follows:

1. The median for each monitoring run was calculated in each zone.
2. The month-year median of monitoring run medians in each was zone was calculated.
3. The season-year geometric mean of month-year medians was calculated for each zone.
4. The upper 99% confident limit (U99CL) of the arithmetic mean of season-year geometric means was calculated for each zone.
5. The following equations were used to calculate the baseline seasonal central tendency of JMSTFU and JMSTFL, respectively, with factors corresponding to the relative aerial proportion of each zone:

JMSTFU baseline central tendency = U99CL of upstream zone * 0.41 + U99CL of downstream zone * 0.59

JMSTFL baseline central tendency = U99CL of upstream zone * 0.49 + U99CL of downstream zone * 0.51

Table 5a. Estimated baseline central tendencies for JMSTFU

Season Year	Upper Zone Mean	Data Source	Lower Zone Mean	Data Source
Spring 2005	2	monthly Dataflow	4	monthly Dataflow
Spring 2006	3	monthly Dataflow	10	monthly Dataflow
Spring 2007	2	monthly Dataflow	8	monthly Dataflow
Spring 2008	3	monthly Dataflow	4	monthly Dataflow
Spring 2009	1	TF5.2, TF5.2A,TF5.3	11	TF5.5, TF5.5A
Spring 2010	4	TF5.2, TF5.2A,TF5.3	5	TF5.5, TF5.5A
Spring 2011	2	TF5.2, TF5.2A,TF5.3	10	TF5.5, TF5.5A
Spring 2012	1	TF5.2, TF5.2A,TF5.3	16	TF5.5, TF5.5A
Spring 2013	2	TF5.2, TF5.2A,TF5.3	6	TF5.5, TF5.5A
Spring 2014	3	TF5.2, TF5.2A,TF5.3	5	TF5.5, TF5.5A
Spring 2015	2	TF5.2, TF5.2A,TF5.3	7	TF5.5, TF5.5A
zone mean	**2**		**8**	
zone U99CL	**3**		**11**	
JMSTFU spring baseline		**8**		
Season Year	**Upper Zone Mean**	**Data Source**	**Lower Zone Mean**	**Data Source**
Summer 2005	5	monthly Dataflow	17	monthly Dataflow
Summer 2006	5	monthly Dataflow	14	monthly Dataflow
Summer 2007	5	monthly Dataflow	16	monthly Dataflow
Summer 2008	7	monthly Dataflow	15	monthly Dataflow
Summer 2009	11	TF5.2, TF5.2A,TF5.3	36	TF5.5, TF5.5A
Summer 2010	14	TF5.2, TF5.2A,TF5.3	43	TF5.5, TF5.5A
Summer 2011	6	TF5.2, TF5.2A,TF5.3*	30	JMS85*
Summer 2012	4	TF5.2, TF5.2A,TF5.3*	22	JMS85*
Summer 2013	3	TF5.2, TF5.2A,TF5.3*	23	TF5.5, TF5.5A
Summer 2014	5	TF5.2, TF5.2A,TF5.3	25	TF5.5, TF5.5A
Summer 2015	4	TF5.2, TF5.2A,TF5.3	29	TF5.5, TF5.5A
zone mean	**6**		**24**	
zone U99CL	**9**		**32**	
JMSTFU summer baseline		**23**		

*These stations were monitored on a weekly basis. JMS85 was monitored exclusively by VCU.

Table 5b. Estimated baseline central tendencies for JMSTFL

Season Year	Upper Zone Mean	Data Source	Lower Zone Mean	Data Source
Spring 2005	6	monthly Dataflow	4	monthly Dataflow
Spring 2006	14	monthly Dataflow	4	monthly Dataflow
Spring 2007	9	monthly Dataflow	3	monthly Dataflow
Spring 2008	5	monthly Dataflow	5	monthly Dataflow
Spring 2009	11	TF5.5, TF5.5A	4	TF5.6
Spring 2010	5	TF5.5, TF5.5A	3	TF5.6
Spring 2011	10	TF5.5, TF5.5A	6	TF5.6
Spring 2012	16	TF5.5, TF5.5A	9	TF5.6
Spring 2013	6	TF5.5, TF5.5A	5	TF5.6
Spring 2014	5	TF5.5, TF5.5A	6	TF5.6
Spring 2015	7	TF5.5, TF5.5A	8	TF5.6
zone mean	**9**		**5**	
zone U99CL	**12**		**7**	
JMSTFL spring baseline		**10**		
Season Year	**Upper Zone Mean**	**Data Source**	**Lower Zone Mean**	**Data Source**
Summer 2005	29	monthly Dataflow	6	monthly Dataflow
Summer 2006	17	monthly Dataflow	5	monthly Dataflow
Summer 2007	17	monthly Dataflow	4	monthly Dataflow
Summer 2008	25	monthly Dataflow	12	monthly Dataflow
Summer 2009	36	TF5.5, TF5.5A	9	TF5.6
Summer 2010	43	TF5.5, TF5.5A	7	TF5.6
Summer 2011	43	TF5.5*, TF5.5A*	23	TF5.6*
Summer 2012	39	TF5.5*, TF5.5A*	19	TF5.6*
Summer 2013	31	TF5.5*, TF5.5A*	12	TF5.6*
Summer 2014	25	TF5.5, TF5.5A	13	TF5.6
Summer 2015	29	TF5.5, TF5.5A	28	TF5.6
zone mean	**30**		**12**	
zone U99CL	**38**		**19**	
JMSTFL summer baseline		**28**		

*These stations were monitored on a weekly basis.

Table 5c. Estimated baseline central tendencies for JMSOH (left) and JMSMH (right)

Season Year	Mean	Data Source
Spring 2005	10	monthly Dataflow
Spring 2006	9	monthly Dataflow
Spring 2007	4	monthly Dataflow
Spring 2008	7	monthly Dataflow
Spring 2009	23	RET5.2, LE5.1
Spring 2010	7	RET5.2, LE5.1
Spring 2011	6	RET5.2, LE5.1
Spring 2012	2	semi-monthly Dataflow
Spring 2013	5	semi-monthly Dataflow
Spring 2014	12	RET5.2, LE5.1
Spring 2015	11	RET5.2, LE5.1
mean	**9**	
U99CL	**13**	
JMSOH spring baseline	**13**	

Season Year	Mean	Data Source
Spring 2005	9	weekly Dataflow
Spring 2006	6	weekly Dataflow
Spring 2007	4	weekly Dataflow
Spring 2008	6	weekly Dataflow
Spring 2009	6	weekly Dataflow
Spring 2010	5	weekly Dataflow
Spring 2011	4	weekly Dataflow
Spring 2012	5	weekly Dataflow
Spring 2013	8	weekly Dataflow
Spring 2014	6	weekly Dataflow
Spring 2015	6	weekly Dataflow
mean	**6**	
U95CL	**7**	
JMSMH spring baseline	**7**	

Season Year	Mean	Data Source
Summer 2005	10	monthly Dataflow
Summer 2006	8	monthly Dataflow
Summer 2007	4	monthly Dataflow
Summer 2008	8	monthly Dataflow
Summer 2009	7	RET5.2, LE5.1
Summer 2010	10	RET5.2, LE5.1
Summer 2011	7	RET5.2, LE5.1
Summer 2012	2	semi-monthly Dataflow
Summer 2013	5	semi-monthly Dataflow
Summer 2014	13	RET5.2, LE5.1
Summer 2015	13	RET5.2, LE5.1
mean	**8**	
U99CL	**11**	
JMSOH summer baseline	**11**	

Season Year	Mean	Data Source
Summer 2005	10	weekly Dataflow
Summer 2006	6	weekly Dataflow
Summer 2007	5	weekly Dataflow
Summer 2008	9	weekly Dataflow
Summer 2009	6	weekly Dataflow
Summer 2010	4	weekly Dataflow
Summer 2011	4	weekly Dataflow
Summer 2012	3	weekly Dataflow
Summer 2013	4	weekly Dataflow
Summer 2014	6	weekly Dataflow
Summer 2015	3	weekly Dataflow
mean	**5**	
U95CL	**7**	
JMSMH summer baseline	**7**	

Table 5d. Estimated baseline central tendencies for JMSPH.

Season Year	Mean	Data Source	Season Year	Mean	Data Source
Spring 2005	12	weekly Dataflow	Summer 2005	9	weekly Dataflow
Spring 2006	5	weekly Dataflow	Summer 2006	6	weekly Dataflow
Spring 2007	7	weekly Dataflow	Summer 2007	7	weekly Dataflow
Spring 2008	5	weekly Dataflow	Summer 2008	8	weekly Dataflow
Spring 2009	6	weekly Dataflow	Summer 2009	8	weekly Dataflow
Spring 2010	10	weekly Dataflow	Summer 2010	3	weekly Dataflow
Spring 2011	6	weekly Dataflow	Summer 2011	5	weekly Dataflow
Spring 2012	4	weekly Dataflow	Summer 2012	8	weekly Dataflow
Spring 2013	5	weekly Dataflow	Summer 2013	6	weekly Dataflow
Spring 2014	9	weekly Dataflow	Summer 2014	6	weekly Dataflow
Spring 2015	5	weekly Dataflow	Summer 2015	5	weekly Dataflow
mean	**7**		**mean**	**6**	
U95CL	**8**		**U95CL**	**8**	
JMSPH spring baseline	**8**		**JMSPH summer baseline**	**8**	

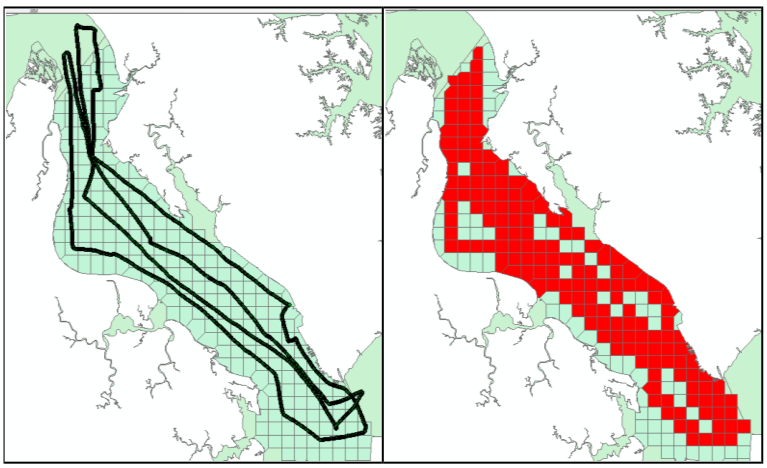


Figure 6. Dataflow dataset aggregation using the Chesapeake Bay Interpolator Grid. A median chlorophyll-a value is generated for each cell traversed by the cruisetrack (cells shown in red).

For each Dataflow cruise, observations were aggregated using the Chesapeake Bay Interpolator grid (see example in Figure 6). The median was calculated of all chlorophyll-a observations taken in a grid cell during a cruise. The median of cell values was then used to represent the spatial central tendency of chlorophyll-a for that cruise.

Baseline Spatial Variation Estimation

Dataflow datasets were used to estimate the baseline spatial variation of chlorophyll-a in each segment. Although the James River datasets are not always lognormally distributed, the geometric standard deviation was chosen to characterize spatial variation based on the work of Campbell (1995) demonstrating that lognormality is a safe and useful assumption for the spatial distribution of chlorophyll-a.

For each Dataflow dataset, grid cell chlorophyll-a medians were log-transformed and the cruise standard deviation was calculated. The upper 95% upper confident limit of the arithmetic mean of these standard deviations was calculated for each segment (and segment-zone, where applicable) and season (shown in Table 6).

Table 6. Estimated baseline spatial (natural-log) standard deviations by segment-season.

Segment-Season	n	Mean STDEV	U95CL STDEV
JMSTFU-upper Spring	7	0.777120126	0.907474087
JMSTFU-lower Spring	7	0.438874854	0.601119083
JMSTFU-upper Summer	12	0.664861671	0.862493318
JMSTFU-lower Summer	12	0.215986406	0.269303315
JMSTFL-upper Spring	8	0.202910226	0.256669097
JMSTFL-lower Spring	8	0.376454591	0.505667971
JMSTFL-upper Summer	12	0.204580228	0.240021506
JMSTFL-lower Summer	12	0.385486598	0.43109373
JMSOH Spring	25	0.382245794	0.466012756
JMSOH Summer	36	0.463815852	0.527822443
JMSMH Spring	137	0.727230915	0.785782579
JMSMH Summer	141	0.693756536	0.743328102
JMSPH Spring	135	0.355468822	0.385723059
JMSPH Summer	147	0.38086044	0.417056998

Baseline Temporal Variation Estimation

For the tidal fresh and JMSOH segments, continuous monitoring datasets were used to estimate the typical seasonal variation of chlorophyll-a (shown in Table 7). The median of all 15-minute chlorophyll-a estimates was calculated over each 24-hour period, and the resulting daily medians were then log-transformed. Standard deviations were calculated for each season-year. Then the upper 95% confidence limit of the arithmetic mean of these standard deviations was calculated for each segment (or segment-zone) and season. Because chlorophyll-a expression in the lower portion of JMSTFU is more like that of the upper portion of JMSTFL than the upper portion of JMSTFU, the temporal standard deviation estimated for upper JMSTFL was also used for the lower portion of JMSTFU. The temporal standard deviation estimates for JMSOH were used for the lower portion of JMSTFL since fixed station datasets suggest that chlorophyll-a concentrations in these areas are more synchronous to each other than concentrations in the lower JMSTFL and upper JMSTFL are.

Table 7. Estimated baseline temporal (natural-log) standard deviations by segment- season.

Segment-Season	n	Mean STDEV	U95CL
JMSTFU-upper Spring	3	0.69104397	0.903940312
JMSTFU-lower Spring	3	0.527053568	0.68267773
JMSTFU-upper Summer	3	0.512128202	0.71778251
JMSTFU-lower Summer	3	0.313900711	0.396182296
JMSTFL-upper Spring	3	0.527053568	0.68267773
JMSTFL-lower Spring	3	0.400438846	0.424532847
JMSTFL-upper Summer	3	0.313900711	0.396182296
JMSTFL-lower Summer	3	0.313371862	0.386876437
JMSOH Spring	3	0.400438846	0.424532847
JMSOH Summer	3	0.313371862	0.386876437
JMSMH Spring	11	0.888583538	0.938333876
JMSMH Summer	11	0.75198526	0.795695085
JMSPH Spring	11	0.576054936	0.713006181
JMSPH Summer	11	0.623283494	0.771890104

For JMSMH and JMSPH, weekly Dataflow datasets were collected. Although not as “high frequency” as continuous datasets, they have a frequency high enough to enable the robust estimation of seasonal variability. Moreover, because a similar cruise track was followed for each cruise, the estimation of seasonal variability can be done at many locations rather than just one. Over each season-year of the baseline period, the standard deviation of log-transformed grid cell medians was calculated, and the upper 95% confidence limit of the arithmetic mean of these standard deviations was calculated for JMSMH and JMSPH. Then the average of these values was used to represent the baseline seasonal variability for each of these two segments.

Chlorophyll-Effect Relationships

The stressor-response concept (see USEPA, 2010b) was used to determine the nature of relationships between chlorophyll-a and HAB occurrence/toxicity, elevated pH, hypoxia, and reduced water clarity in the James River. Whenever possible, conventional statistical models (non-linear, linear, and logistic regression) were employed to simulate relationships, as these kinds of models facilitate replication of results, reporting of relationship strength and prediction uncertainty, and concise graphical displays. Model variables were transformed whenever appropriate to maximize model fitness. Root mean square error and R^2 (R^2 for ordinary least square regressions and McFadden R^2 for all other regressions) were used to select the best model.

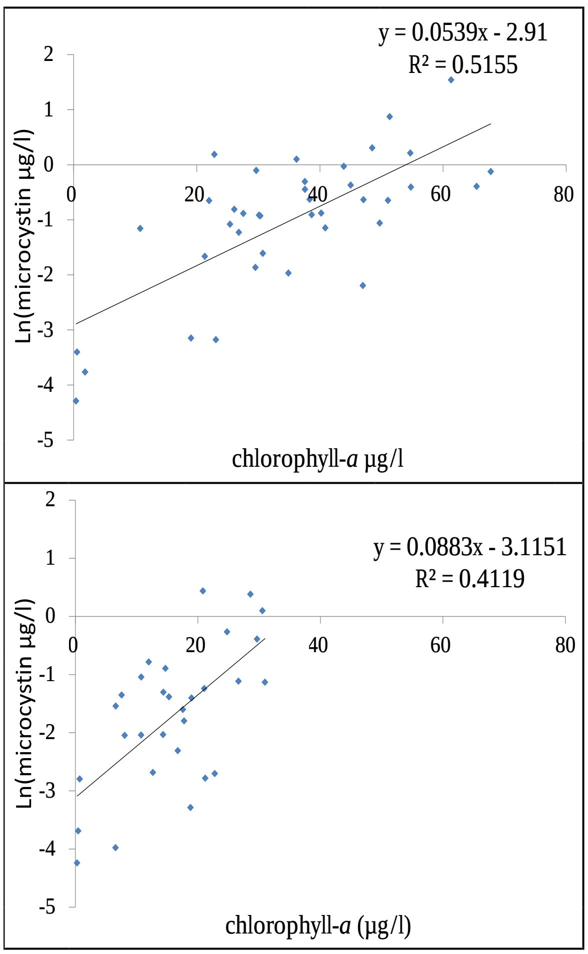


Figure 7. Scatterplots of chlorophyll-a and microcystin concentrations. Top) Samples collected at station TF5.5A (upper portion of JMSTFL). Bottom) Samples collected at station TF5.6 (lower portion of JMSTFL).

Harmful Algal Bloom Metrics

JMSTFU (upper zone)

Extracellular microcystin samples collected at TF5.3 are significantly correlated with chlorophyll-a samples. However, microcystin samples were well below the effect threshold (1 µ/L). For this reason, it is assumed microcystin is not a threat to the aquatic life in the upper portion of JMSTFU.

JMSTFU (lower zone) and JMSTFL (upper zone)

The relationship between chlorophyll-a and microcystin was modeled using summertime data collected at fixed stations located in the lower portion of JMSTFU and upper portion of JMSTFL. Relationships were modeled using both individual station datasets and different combinations of pooled datasets (e.g., JMS85 + TF5.5, TF5.5 + Rice, TF5.5 + Rice + TF5.5A, etc.) The model with the lowest relative root mean square error was deemed the one with the most predictive power. This model (top panel of Figure 7) was then used to determine the chlorophyll-a concentration associated with the harmful microcystin threshold of 1 µg/L. This concentration is 53 µg/L.

JMSTFL (lower zone)

Samples collected at station TF5.6 were used to model the relationship between summertime water column chlorophyll-a and microcystin concentration in the lower portion of JMSTFL. This model (bottom panel of Figure 7) was then used to determine the chlorophyll-a concentration associated with the harmful microcystin threshold of 1 µg/L. This concentration is 35 µg/L.

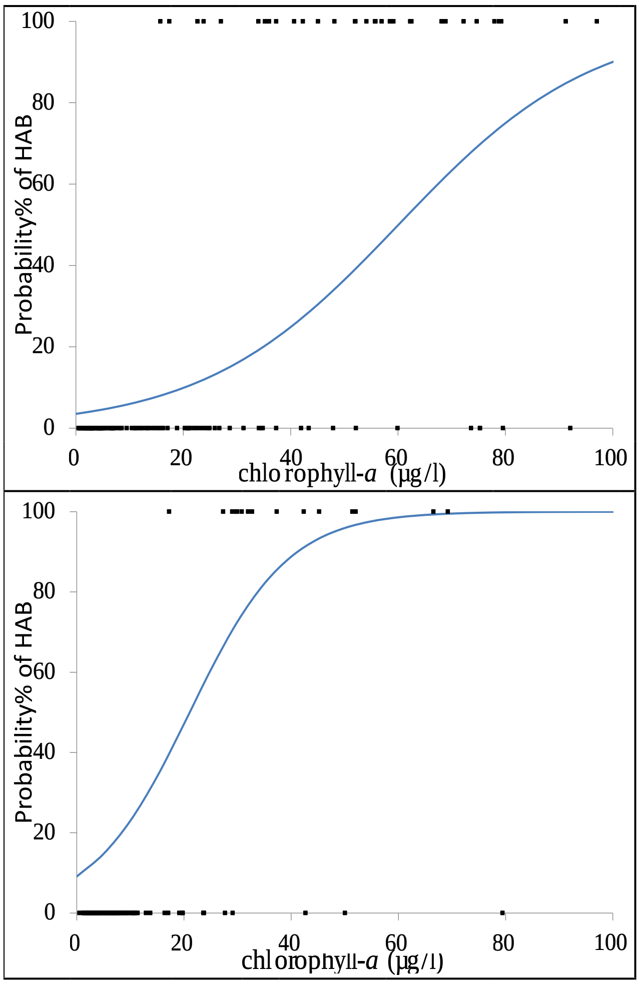


Figure 8. Logistic regression models predicting the probability of harmful cell densities of *C. polykrikoides* over a range of chlorophyll-a concentrations in JMSMH (top) and JMSPH (bottom).

JMSOH

There are very few incidents of harmful algae blooms in the monitoring record for JMSOH. For this reason, no relationship was determined for chlorophyll-a and HAB metrics in this segment.

JMSMH

The relationship between chlorophyll-a and cell densities of the toxic dinoflagellate *Cochlodinium polykrikoides* was modeled using samples (n=262) collected throughout JMSMH during summertime Dataflow cruises. A logistic regression model[9] (top panel of Figure 8) predicts a high risk of harmful cell densities (1,000 cells/ml) at a chlorophyll-a concentration of 60 µg/L.

JMSPH

The relationship between chlorophyll-a and cell densities of *C. polykrikoides* was

[9] Negative binomial regression models are appropriate for the *C.polykikroides* datasets given the count variable, the abundance of zeros, and overdispersion in the datasets. However, the model fits were superior using logistic regression as indicated by the McFadden R^2 (0.424 versus -478.614 for JMSMH, 0.629 versus -397.810 for JMSPH).

modeled using samples (n=147) collected throughout JMSPH during summertime Dataflow cruises. A logistic regression model[9] (bottom panel of Figure 8) predicts a high risk (50% probability) of harmful cell densities (1,000 cells/ml) at a chlorophyll-a concentration of 21 µg/L.

Elevated pH

The relationship between chlorophyll-a and pH was discerned through the use of continuous monitoring datasets. Fifteen-minute observations were aggregated over 24-hour periods (median for chlorophyll-a and 90th percentile for pH). A spacing interval of five days was used to limit temporal dependency between daily "samples".

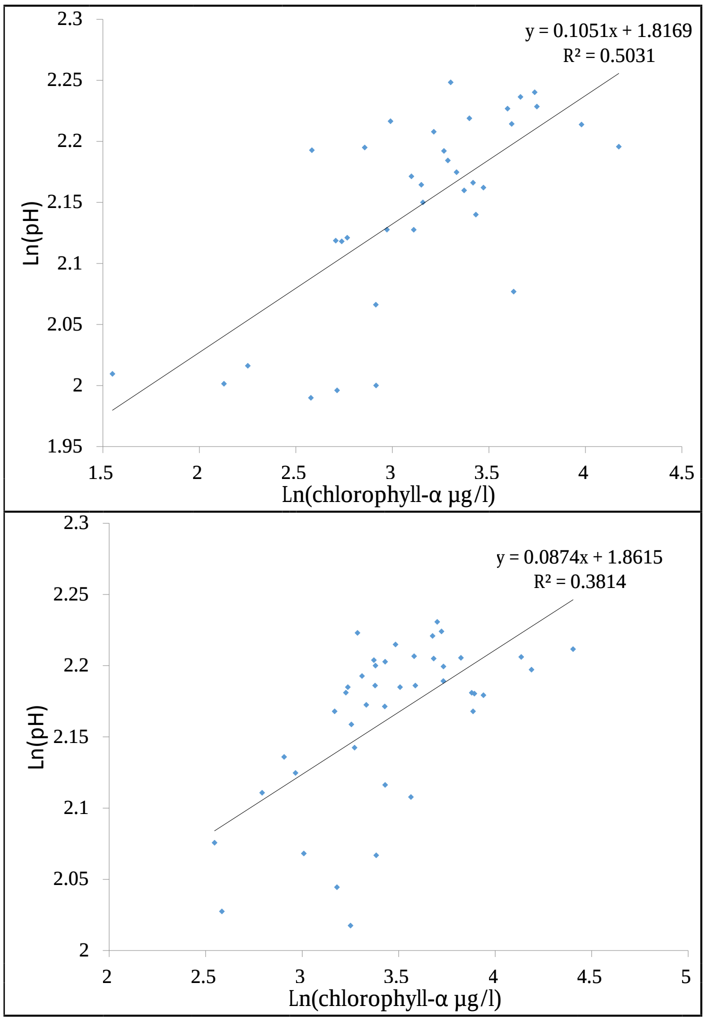


Figure 9. Scatterplot of pH (daily 90th percentile) and chlorophyll-a concentration (daily median) from continuous data taken in the upper zone of JMSTFL during the spring (top) and summer (bottom).

JMSTFU (upper zone)

Because none of observations of pH recorded by the continuous monitor deployed in the upper portion of JMSTFU were higher than 8.9—below the effect threshold of 9.1—elevated pH is assumed to be an unlikely stressor of aquatic life in the upper portion of JMSTFU.

JMSTFU (lower zone) and JMSTFL (upper zone)

According to the linear regression model based on continuous monitoring data collected in the upper zone of JMSTFL (top panel of Figure 9), the chlorophyll-a concentration linked to a high risk of elevated pH (>=9.1) was determined to be 40 µg/L for the spring and 50 µg/L for the summer.

JMSTFL (lower zone)

Continuous data are not available for the lower zone of JMSTFL. However, since monitoring began in 1985, elevated pH has been observed only once in grab samples taken from TF5.6.

For this reason, elevated pH is assumed to be an unlikely stressor of aquatic life in this portion of the estuary.

JMSOH

According to the linear regression model based on continuous monitoring data collected in JMSOH (Figure 10), the chlorophyll-a concentration linked to high risk of elevated pH (>=9.1) was determined to be 40 µg/L for the spring and 28 µg/L for the summer.

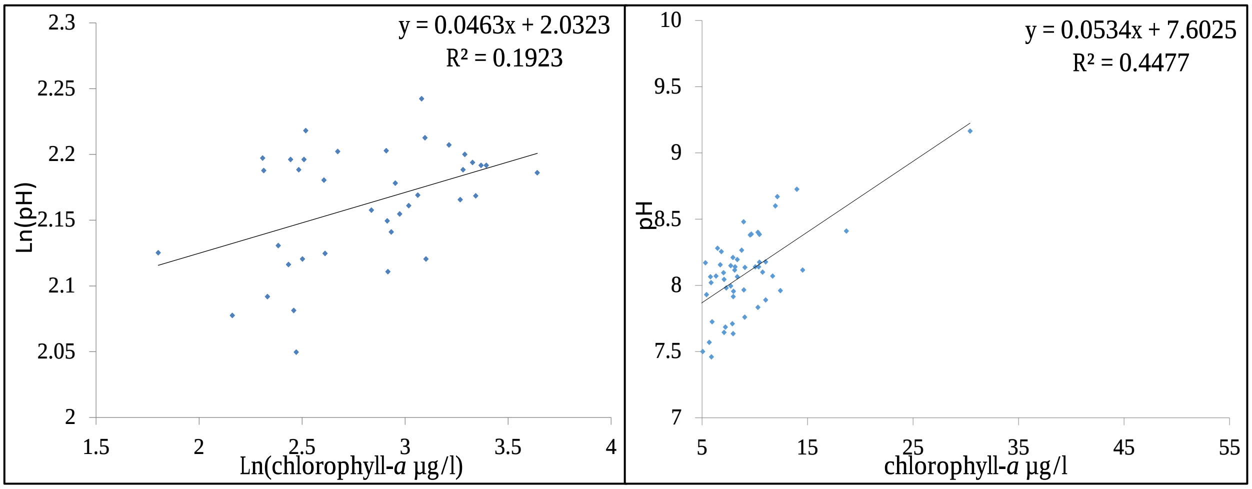


Figure 10. Scatterplot of pH (daily 90th percentile) and chlorophyll-a concentration (daily median) from continuous data collected in JMSOH during the spring (left) and summer (right).

JMSMH

Elevated pH (>= 9.1) was observed in JMSMH via continuous monitors, but only at chlorophyll-a concentrations greater than 100 µg/L. Concentrations this high occur very rarely. For this reason, elevated pH is assumed to be an unlikely stressor of aquatic life in this segment.

JMSPH

Because no observations of pH recorded by the continuous monitor deployed in JMSPH were higher than 9.0, elevated pH is assumed to be an unlikely stressor of aquatic life in this segment.

Low Dissolved Oxygen

Using long-term monthly fixed station datasets spanning 1991 to 2015, bottom measurements of dissolved oxygen were related to surface measures of chlorophyll-a for segments and segment-zones where hypoxia has been reported on multiple occasions. DO concentrations were converted to DO percent saturation, since the latter is not confounded by the effect temperature has on oxygen solubility. Chlorophyll-a was averaged over the spring and summer months and related to summertime DO percent saturation since previous estuarine studies have shown that negative correlations between summer DO and chlorophyll-a are likely to be evident when the latter is integrated over multiple seasons rather than just one (Harding et al., 2014; Sutula et al.,2017)[10].

JMSTFU (upper zone)

Summer hypoxia in JMSTFU has only been reported once (VADEQ, 2010) since the Chesapeake Bay dissolved oxygen standards were first implemented in 2006 (VSWCB, 2011). For this reason, it is unlikely that algal-related low DO is a stressor of aquatic life in this part of the estuary.

JMSTFU (lower zone) and JMSTFL (upper zone)

Chronic summer hypoxia in JMSTFL has been reported since the Chesapeake Bay dissolved oxygen standards were first implemented in 2006 (VADEQ, 2006, 2008, 2010, 2012, and 2016a), specifically violations of the 30-Day Mean criterion for the Open Water sub-use (5.5 mg/L). However, as shown in Figure 11, no significant correlations were found between spring-summer chlorophyll-a and summer DO at stations TF5.5 and TF5.5A. Thus, no effect for

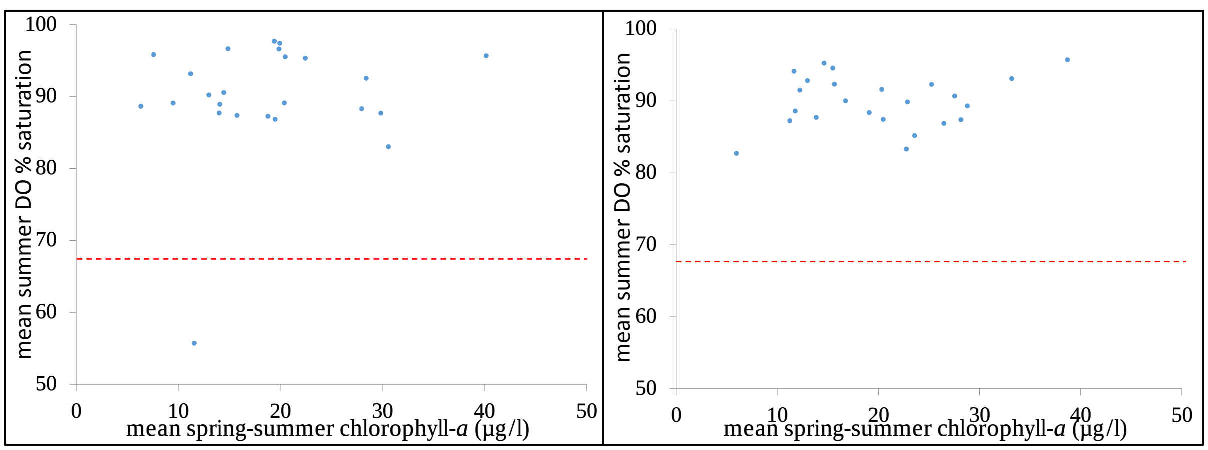


Figure 11. Scatterplot of summer DO percent saturation versus the geometric mean of spring-summer chlorophyll-a at stations TF5.5 (left) and TF5.5A (right). Red line indicates the threshold (68%) corresponding to the 30-Day Mean criterion (5.5 mg/l), assuming average summer temperature of 26˚C, average sea-level pressure 760 mmHg, and average salinity of 0 ppt.

[10] Relationships between chlorophyll-a and DO were examined using other approaches besides the one presented here. Appendix B presents the results of those other approaches.

chlorophyll-a can be discerned in relation to low DO for this part of the estuary.

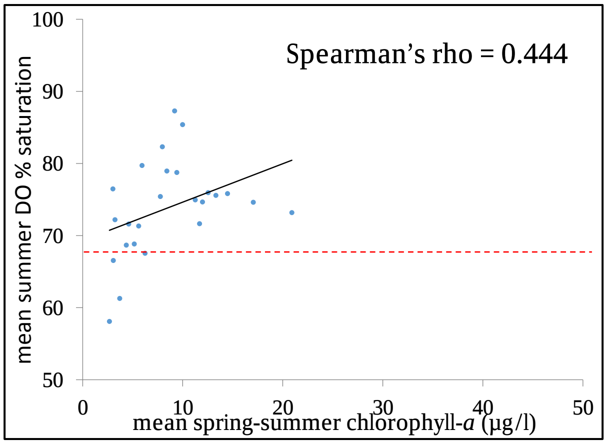


Figure 12. Scatterplot of summer DO percent saturation versus the geometric mean of spring-summer chlorophyll-a at TF5.6. Red line indicates the threshold (68%) corresponding to the 30-Day Mean criterion (5.5 mg/l), assuming average summer temperature of 26˚C , average sea-level pressure 760 mmHg, and an average salinity of 0 ppt.

JMSTFL (lower zone)

Most instances of low DO concentration (< 5.5 mg/L) reported in JMSTFL over the 1991 to 2015 period have been observed at TF5.6, which is located in the lower portion of JMSTFL. In contrast to what was found for the other two JMSTFL station datasets, a significant correlation ($p<0.05$) between DO and chlorophyll-a was detected at TF5.6. However, it is a positive correlation, as shown in Figure 12. Thus, no effect concentration for chlorophyll-a can be discerned in relation to low DO for this part of the estuary.

JMSOH

Summer chronic hypoxia in JMSOH has been reported three times (VADEQ, 2006, 2010, 2016) since the Chesapeake Bay dissolved oxygen standards were first implemented in 2006, specifically violations of the 30-Day Mean criterion for the Open Water sub-use (5.0 or 5.5 mg/L, depending on observed salinity). However, no relationship is discernible between summer DO percent saturation and spring-summer chlorophyll-a at either station RET5.2 or LE5.1 (Figure 13). Thus, no effect concentration for chlorophyll-a can be discerned in relation to low DO.

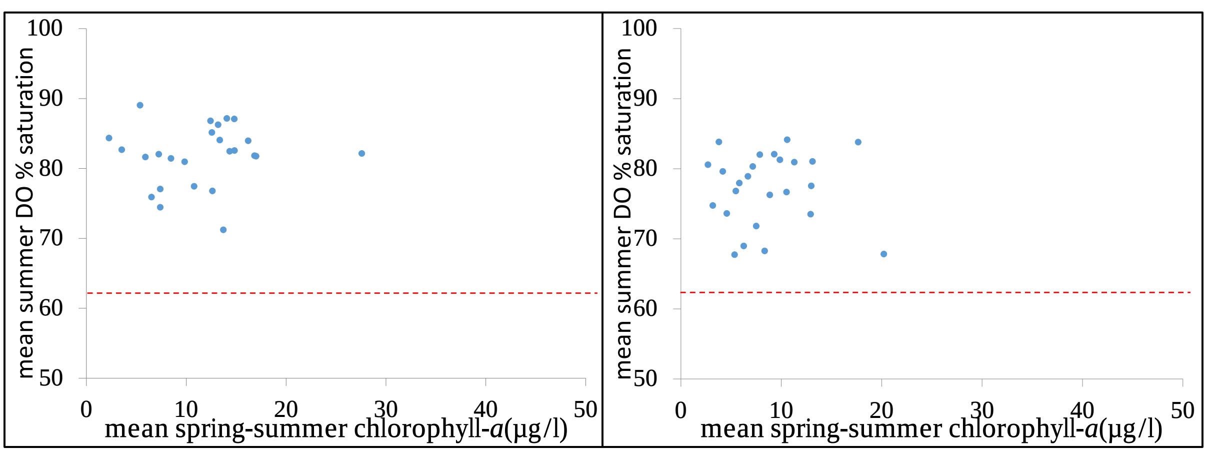


Figure 13. Scatterplot of summer DO percent saturation versus the geometric mean of spring-summer chlorophyll-a at RET5.2 (left) and LE5.1 (right). Red line indicates the threshold (63%) corresponding to the 30-Day Mean criterion (5.0 mg/l), assuming average summer temperature of 26˚C, average sea-level pressure 760 mmHg, and average salinity of 3 and 6 ppt, respectively .

JMSMH

Summer chronic hypoxia in JMSMH has been reported three times (VADEQ, 2006, 2008, 2010) since the Chesapeake Bay dissolved oxygen standards were first implemented in 2006, specifically violations of the 30-Day Mean criterion for the Open Water sub-use (5.0 mg/L). However, no relationship is discernible between summer DO percent saturation and spring-summer chlorophyll-a at either station LE5.3 or LE5.4 (Figure 14). Thus, no effect concentration for chlorophyll-a can be discerned in relation to low DO for this segment.

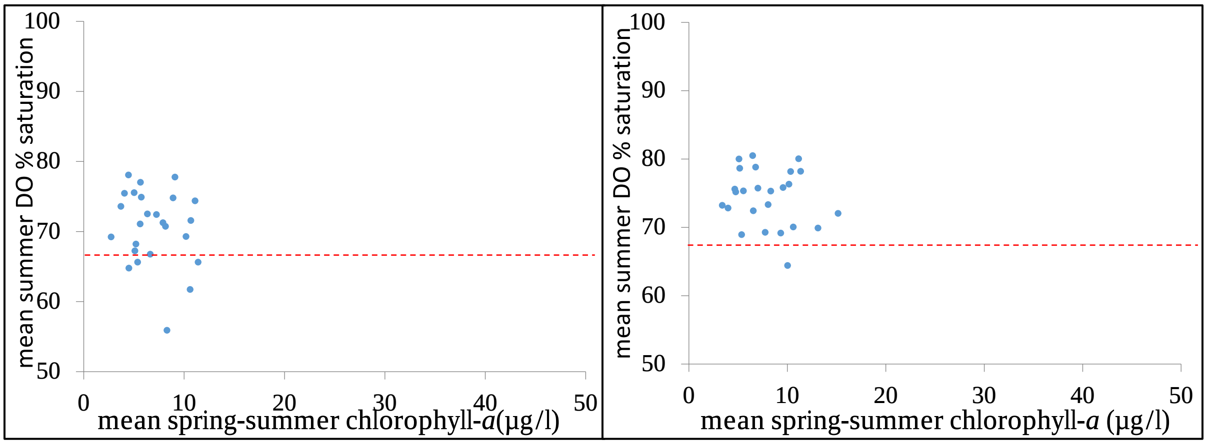


Figure 14. Scatterplot of summer DO percent saturation versus the geometric mean of spring-summer chlorophyll-a at LE5.2 (left) and LE5.3 (right). Red line indicates the threshold (67% and 68%) corresponding to the 30-Day Mean criterion (5.0 mg/l), assuming average summer temperature of 26°C, average sea-level pressure 760 mmHg, and an average salinity of 14 and 18 ppt, respectively.

JMSPH

To date, chronic hypoxia in JMSPH has not been reported. Thus, it is unlikely that algal-related low DO is a stressor of aquatic life in this segment.

Poor Water Clarity

A number of published Chesapeake Bay-specific optical models were examined (see Appendix C) to elucidate the relationship between James River chlorophyll-a, total suspended solids (TSS) or turbidity, and the light attenuation coefficient K_d—a metric of water clarity. But (not surprisingly) the model[11] that produced the most accurate predictions of K_d was derived solely from James River water quality samples (spring and summer, 1993 to 2010):

Predicted K_d = 0.295344 + 0.014785*[chlorophyll-a µg/L] - 0.00229*[salinity ppt] + 0.326669*[turbidity NTU]^0.6667 (Equation 1)

[11] This model is informed by Elgin Perry's analysis described in USEPA (2008).

Equation 1 was used to find the maximum growing season average chlorophyll-a concentration that supports optimal K_d in each segment (see Table 8). Fixed station datasets were used to create segment (and segment-zone) specific regressions of TSS and turbidity. These relationships were used in conjunction with Equation IV-11 from Batiuk et al. (2000) to generate site-specific estimates of phytoplankton-related turbidity. For the tidal fresh and oligohaline segments, which have a percent-light-through-water requirement of 13%, the K_d values of 2.0 and 1.0 m^{-1} are considered optimal for SAV growth at the 1-meter and 2-meter application depths, respectively. For the meso- and polyhaline segments, which have a percent-light-through-water requirement of 22%, the K_d values of 1.5 and 0.8 m are considered optimal for SAV growth at the 1-meter and 2-meter application depths, respectively.

Table 8. Maximum chlorophyll-a concentrations (as growing season averages) predicted to support optimal Kd at the 1-m and 2-m application depths. Asterisks indicate cases where optimal K_d is predicted to be unattainable even when chlorophyll-a is equal to zero.

Segment	Average salinity (ppt)	Relationship of turbidity to TSS	Chlorophyll-*a* (µg/l) supporting optimal K_d @ 1-meter	2-meter
JMSTFU upper	0	0.934 x TSS	46	16
JMSTFU lower	0	4.449 + 0.6897 x TSS	32	*
JMSTFL upper	0	4.449 + 0.6897 x TSS	32	*
JMSTFL lower	0	1.127 x TSS	42	14
JMSOH	4	0.9601 x TSS	46	16
JMSMH	18	0.741 x TSS	34	12
JMSPH	22	3.605 + 0.324 x TSS	22	*

Evaluation of Baseline Central Tendency Protectiveness

The aforementioned empirical relationships were used to pinpoint "high risk" chlorophyll-a concentrations (see Table 9)—those concentrations associated with the various effect thresholds shown in Table 3. These chlorophyll-a values are crucial for determining whether the baseline central tendencies are protective.

To establish whether baseline central tendencies are protective against a long-term effect of poor water quality, the "high risk" spring-summer chlorophyll-a means were compared to the baseline spring-summer means. If the baseline spring-summer mean for a segment is less than or equal to the "high-risk" threshold, then the former is considered protective. There were no baseline spring-summer means that were higher their respective "high risk" threshold.

Table 9. "High risk" chlorophyll-a concentrations (µg/L) for various effects in the James river segments, as determined by empirical models.

	Short-Term Effects			Long-Term Effects			Baseline Central Tendency		
	HABs	Elevated pH		Low DO	Poor Water Clarity				
Season	**Summer**	**Spring**	**Summer**	**Spring-Summer**	**Spring-Summer**		**Spring**	**Summer**	**Spring-Summer**
Application Depth					1-m	2-m			
JMSTFU upper	NA	NA	NA	NA	>46	>16	3	9	5
JMSTFU lower	>=53	>=40	>=50	ND	>32	*	11	32	19
JMSTFL upper	>=53	>=40	>=50	ND	>32	*	12	38	21
JMSTFL lower	>=35	NA	NA	ND	>42	>14	7	19	12
JMSOH	NA	>=40	>=28	ND	>46	>16	13	11	12
JMSMH	>=60	NA	NA	ND	>34	>12	7	7	7
JMSPH	>=21	NA	NA	NA	>22	*	8	8	8

NA = not applicable since the harmful effect has never or very rarely been observed in the segment/segment-zone.
ND = none determined since no statistically significant relationship between chlorophyll-a and harmful effect was detected.
* = Empirical model indicates harmful effect will occur even in the absence of chlorophyll-a.

For each short-term aquatic life effect, such as elevated pH, it is assumed that the aquatic life use can withstand up to a 10% incident rate or a 10% probability of occurrence (USEPA, 2003a). If these effects were to occur more frequently than 10% of the time, then the classification of the aquatic life use as "impaired" would be justified. To predict the frequency of short-term "high risk" chlorophyll-a values at baseline central tendency and variability, a cumulative distribution function was composed for each segment/segment-zone using log-normalized parameters. Because these segments/segment-zones are large and chlorophyll-a so spatially "patchy", CDFs were also used to determine the percentage of habitat "at risk" of harmful effect, given a "high risk" chlorophyll-a concentration (natural-log of values shown in Table 9), baseline central tendency (natural-log of spring and summer central tendency values shown in Table 9), and baseline spatial standard deviation (values shown in Table 6). Central tendencies are considered protective if they are predicted to confer harmful effects less than or equal to 10% of the time and in less than or equal to 10% of the habitat. In those cases where the baseline central tendencies are linked to exposure rates greater than 10%, the segment-season specific CFDS were used to select protective central tendencies (example shown in Figure 15). Baseline summer means for JMSTFU-lower, JMSTFL-upper, and JMSPH were all found to have unacceptably high risks of elevated pH (tidal fresh segments) and HABs (JMSTFL-upper and JMSPH); thus, more protective means were sought for these segments (shown in Table 10). No baseline spring means were found to be unprotective.

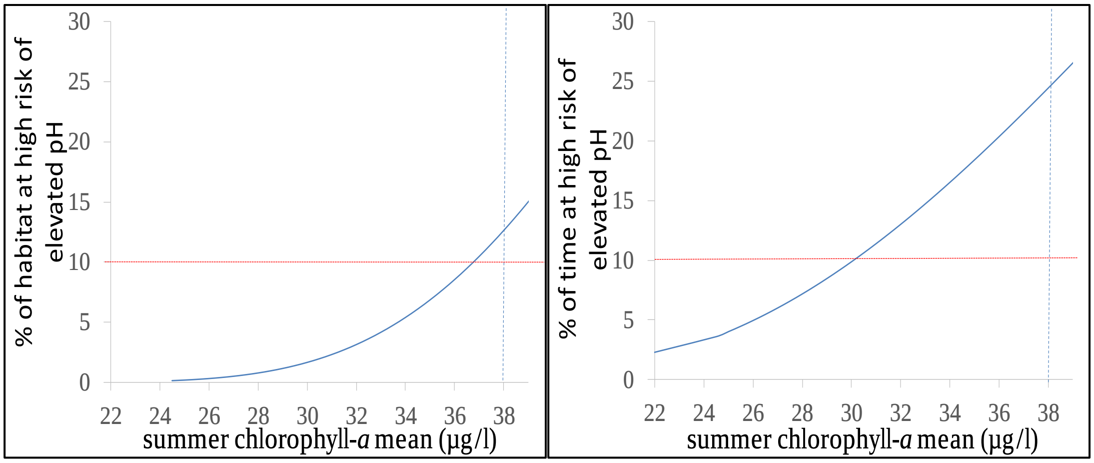


Figure 15. CDFs used to determine the protective central tendency for JMSTFL-upper in relation to summertime elevated pH in space (left) and time (right). Red line indicates the acceptable risk level and the vertical blue line indicates the baseline central tendency.

Table 10. Expected frequencies of "high risk" chlorophyll-a concentrations for HABs (top) and elevated pH (middle and bottom) in segments/segment-zones where harmful effects have been observed.

Segment	Summer "high risk" concentration for HABs (µg/l)	Probability of Exceedence at Baseline %space	%time	Baseline Summer Central Tendency	Protective* Summer Central Tendency
JMSTFU lower	>=53	<1%	10%	32	32
JMSTFL upper	>=53	8%	20%	38	32
JMSTFL lower	>=35	7%	6%	19	19
JMSMH	>=60	<1%	<1%	7	7
JMSPH	>=21	2%	11%	8	<u>7</u>

Segment	Spring "high risk" concentration for pH (µg/l)	Probability of Exceedence at Baseline %space	%time	Baseline Spring Central Tendency	Protective* Spring Central Tendency
JMSTFU lower	>=40	<1%	3%	11	11
JMSTFL upper	>=40	<1%	4%	12	12
JMSOH	>=40	1%	<1%	13	13

Segment	Summer "high risk" concentration for pH (µg/l)	Probability of Exceedence at Baseline %space	%time	Baseline Summer Central Tendency	Protective* Summer Central Tendency
JMSTFU lower	>=50	1%	24%	32	<u>30</u>
JMSTFL upper	>=50	12%	24%	38	<u>30</u>
JMSOH	>=28	4%	1%	11	11

* The lowest protective central tendency for a segment- season is the recommended criterion for that segment-season. These values are underlined.

Recommended Criteria

Tables 11a and 11b present the recommended updated James River chlorophyll-a criteria, which when applied in a manner consistent with their derivation should provide adequate protection of the aquatic life designated use. Recommended seasonal mean criteria should not be exceeded more than twice in six years, and the recommended short-duration criteria should not be exceeded more than 10% of the time over six years.

Table 11a. Recommended James River seasonal mean chlorophyll-a criteria.

Segment-Season	2005 Criteria	Recommended	Basis for recommended criteria lower than baseline
JMSTFU-spring[1]	10	8	
JMSTFU-summer[1]	15	21	Enhanced protection from elevated pH
JMSTFL-spring[2]	15	10	
JMSTFL-summer[2]	23	24	Enhanced protection from elevated pH and harmful algal blooms
JMSOH-spring	15	13	
JMSOH-summer	22	11	
JMSMH-spring	12	7	
JMSMH-summer	10	7	
JMSPH-spring	12	8	
JMSPH-summer	10	7	Enhanced protection from harmful algal blooms

[1] Recommended JMSTFU criterion = (upper zone baseline central tendency)*0.41 + (lower zone protective central tendency) * 0.59
[2] Recommended JMSTFL criterion = (upper zone protective central tendency)*0.49 + (lower zone baseline central tendency)*0.51

Table 11b. Recommended James River short-duration chlorophyll-a criteria, applicable during the summer only to protect aquatic life from the effects of toxic harmful algal blooms.

Segment	Spatial Application	Magnitude	Duration[1]
JMSTFU	Lower zone of JMSTFU	52	1-month median
JMSTFL	Upper zone of JMSTFL	52	1-month median
JMSTFL	Lower zone of JMSTFL	34	1-month median
JMSOH	Entire segment	--	--
JMSMH	Entire segment	59	1-day median
JMSPH	Entire segment	20	1-day median

[1] The recommended durations are informed by (but not direct reflections of) the exposure times used in the toxicity studies underlying the HAB effect thresholds enumerated in Table 3.

DISCUSSION

As shown in Table 11a, most of the recommended seasonal mean criteria are lower than the 2005 criteria. The difference can be attributed partially to the more recent, more sophisticated datasets used to characterize current conditions. The 2005 seasonal mean criteria were derived using information generated solely at fixed stations since spatially-intensive datasets were not available at the time of their development. While fixed stations are adequate for tracking long-term trends, they do not always represent their respective segments very well. This is apparent with the complement of long-term stations in JMSTFU (TF5.2, TF5.2A, and TF5.3), which are all located in an area of the segment where chlorophyll-a concentrations are very low relative to the levels expressed just a few miles downstream. Because Dataflow datasets cover the full extent of a segment, they enable a more accurate characterization of chlorophyll-a expression than what fixed station datasets provide. In most segments, it appears that the fixed station datasets tend to show higher chlorophyll-a concentrations compared to the Dataflow datasets, which may partially explain why most of the baseline criteria are substantially lower than their respective 2005 criteria. But because the fixed station datasets in JMSTFU grossly underestimate the segment baseline, the revised summer seasonal mean criterion is considerably higher than the 2005 criterion for this segment. This should not be viewed as a relaxation of protection, but rather as a correction now that more information is available for JMSTFU.

In addition, the measures of central tendency used for the 2005 and revised seasonal mean criteria are not the same. Arithmetic means were used to derive the 2005 criteria, but since that time research has shown that the central tendency of James River chlorophyll-a is best captured by the geometric mean (USEPA, 2010a). Arithmetic means almost always produce higher estimates than geometric means due to their greater sensitivity to outliers, further explaining why almost all the 2005 seasonal mean criteria are higher than the revised criteria. To illustrate, for JMSPH, chlorophyll-a expressed as a geometric mean is estimated to be 8 µg/L at the summer baseline. When expressed as an arithmetic mean, the estimate is 12 µg/L. Because criteria are the vehicle for setting watershed pollutant loads, it is crucial they be the most accurate reflections of the regulatory target(s) of concern.

There are other differences in how the two criteria were derived. Firstly, the 2005 seasonal mean criteria were derived using data compiled from all waters of the Chesapeake Bay, including the mainstem, rather than exclusively from the James River. While the James shares similarities with the other Bay tributaries, it has certain features—like its higher sediment load (USAEPA, 2010c) and lower residence times (Bricker et al., 2007) —that make it deserving of more individualized treatment. Secondly, the 2005 criteria were derived for the purposes of "fish food" protection, not protection against lethal HABs or physicochemical impacts. The more explicit endpoints of the revised criteria require more precision. Lastly, the protectiveness of the 2005 criteria with respect to hypoxia was not addressed, since hypoxia in the James River had not been reported when those criteria were being developed. While a relationship between chlorophyll-a and low dissolved oxygen could not be discerned from the available data, the revised criteria do help to ensure that hypoxic incidents do not increase in frequency or grow more intense.

Developing criteria based on the variation observed in monitoring datasets is not a new technique (Walker et al., 1984; Harding et al., 2014). But it is rare when spatially and temporally intensive datasets are both available and are sufficient enough in scope and scale to facilitate the precise targets that were used to re-derive the JRCC. Temporal variability is the most important determinant for criteria protectiveness in most of the James River segments—meaning that as long as criteria are protective 90% of the time, the same proportion or more of the open water habitat will be protected in these segments. The exception is JMSOH, which seems to require criteria that are established on the basis of protection of space before protection of time. Without the site-specific Dataflow and continuous data generated by the partnering institutions VIMS and HRSD, this nuance would be left unappreciated.

The use of baseline metrics for developing nutrient-related criteria is also not a new technique, with states such as Virginia, Florida, and Texas having adopted such criteria for the protection of lakes. But the approach should be used wisely. The James River is an impaired estuary, so one could argue that protecting baseline chlorophyll-a levels could maintain impairment rather providing a means to correct it. This argument rests on a couple of questionable assumptions, however. One of these assumptions is that chlorophyll-a is an indicator of all sources of aquatic life use impairment. The James River has a number of non-nutrient sources of ecological stress, such as excessive sediment load and habitat loss. Degraded benthic and phytoplankton communities have been documented for some time in the James River estuary (see Dauer et al., 2016 for the most recent analysis of status and trends), but an empirical relationship between biotic integrity and chlorophyll-a concentrations is either non- existent or very weak (see Appendix C). Sedimentation (Diaz, 1989) and poor water clarity (Buchanan, 2015) stemming from excessive suspended sediment are largely responsible for degradation in these communities. Non-phytoplankton sources of turbidity probably also explain why the James River optical model (Equation 1) predicts poor water clarity at the 2-m application depth in most of the tidal fresh and in JMSPH even when chlorophyll-a is equal to zero[12]. Attainment of even the most stringent chlorophyll-a criteria would not address impacts stemming from non-nutrient causes.

[12] For much of the tidal fresh, turbidity is the result of TSS and colored dissolved organic matter (CDOM). Thus, removing TSS would still result in reduced water clarity at the 2-m depth contour. This may explain why even historical SAV beds in the tidal fresh (Moore et al, 1999) tended to be isolated to the shallowest portions of the habitat. For JMSPH, the ratio of TSS to turbidity is much higher than it is for other segments. This is may be due to the presence of larger particles in the water column, as JMSPH experiences high turbulence due to its proximity to the ocean. Thus, the dire predictions generated by the optical model for JMSPH may not be accurate. The relatively high levels of SAV coverage in this segment compared to other James River segments (Orth et al., 2017) suggests that this is the case.

Another questionable assumption is that chlorophyll-a concentrations have only continued to worsen throughout the James River since the estuary was first listed as impaired for nutrients in 1999. Two independent trend analyses belie this assumption. The analysis of monthly chlorophyll-a observations using generalized additive models (which indicate trends even when a variable changes in a non-linear fashion) indicates that most of the James River stations have either experienced significantly improving (decreasing) or stable chlorophyll-a concentrations over the 1999 to 2015 time frame. This is corroborated by seasonal Kendall trend analysis of datasets collected over the 1985 to 2017 time period. (A summary of both analyses is presented in Appendix E.) However, both analyses indicate non-improving trends in the lower estuary. Thus, it is reasonable to question whether the recommended criteria for JMSMH and JMSPH could be lower if only the baseline period was delineated differently. To determine if this is the case, the upper 95% confidence limit of the arithmetic mean of segment-season-year geometric means was estimated over the following periods using long-term fixed station datasets: 1986 to 2015, 1986 to 1999, and 2000 to 2015 (see Appendix E). Almost all the recommended baseline criteria are lower than or equal to the central tendency estimates calculated over both the full period of record and the different subset periods, even in JMSMH and JMSPH—where there are signs that chlorophyll-a values are trending upwards. The only exception is the recommended criterion for summer JMSOH, which is slightly higher than the upper 95% confidence limit of the mean for the 2000-2015 period (11 µg/L versus 10 µg/L).

The recommended seasonal mean criteria do assume that chlorophyll-a variability in the James River will rarely exceed the standard deviation values derived from the baseline datasets. The upper 95% confidence limit of the mean of baseline period standard deviation estimates was chosen to represent "typical" variation because this statistic hedges against uncertainty much better than an average (or even a 95th percentile in some cases). If one assumes the baseline datasets are adequately representative of typical conditions, one would expect higher variability than the segment-season estimates shown in Table 6 and Table 7 no more than 2.5% of the time. The lack of spatially and temporally intensive datasets beyond the baseline period makes it impossible to test this assumption. However, we can consult circumstantial evidence. While monthly fixed station datasets are not "dense" enough for quantifying seasonal-year variability in a very robust way, one may be able to still glean overall trends from these datasets. As shown in Appendix G, there are no indications that seasonal standard deviations are increasing in any of the segments. Like all water quality criteria, however, the recommended criteria would need to be revisited on a regular basis to ensure that their underlying assumptions are valid according to what is apparent in contemporaneous datasets. Furthermore, the recommended short-duration criteria ensure protection of aquatic life from toxic HAB events, independent of the seasonal variability of chlorophyll-a.

The exceedance frequency for the proposed criteria differs from the allowable frequency that EPA recommends for aquatic life toxic criteria. EPA assumes that aquatic life can recover from exceedances of toxic criteria as long as they occur once in three years. This interval represents a reasonable middle ground within the range of recovery periods documented by over 150 published studies of freshwater ecosystems challenged by natural and anthropogenic disturbances (EPA, 2003a). For the proposed seasonal mean criteria, VADEQ has proposed to adopt an allowable frequency that maintains the same proportion of exceedance to nonexceedance as the EPA-recommended frequency, but stipulates a longer interval (e.g., two exceedances over six years versus one exceedance over three years). VADEQ believes that in the context of James River chlorophyll-a, the protection to aquatic life offered by the two frequency statements is similar and that the only difference—the spacing of allowed exceedances—is not an important one. That is to say, VADEQ believes allowing two seasonal mean exceedances over a six-year interval, no matter how they are distributed over that interval, will not negatively impact aquatic life recovery. The EPA-recommended frequency rule and VADEQ's proposed frequency rule are equivalent when they are viewed as long-term goals. The implementation of water quality criteria—such as through Total Maximum Daily Load modeling or the design of waste water treatment facilities in response to permit limits—necessitates the interpretation of the frequency statement as a long-term average.

The benefit of VADEQ's proposed frequency rule is that it does not presume that closely spaced exceedances make for a less ideal goal than those spread out by three or more years as long as closely spaced exceedances do not confer serious adverse effects. VADEQ presumes the majority of seasonal mean exceedances will not confer serious adverse effects. There are four arguments that support this assumption:

- **Small exceedances of chlorophyll-a criteria are unlikely to be associated with harm.** EPA's frequency statement ("no more than one exceedance every three years") is recommended specifically in the context of aquatic life toxics criteria. Although toxics criteria are developed quite conservatively, it is not unreasonable to expect that even a small exceedance would cause some degree of harm to aquatic life. Most toxic substances regulated for the protection of aquatic life are insecticides and herbicides; thus, only trace amounts of these substances would ever be considered harmless. Because adverse effects will almost always result from toxic criteria exceedances, a compounding effect is expected when exceedances occur too closely together in time. However, in contrast to toxic substances, chlorophyll-a is a natural substance with no known toxicity. Up to a certain concentration, it is positively correlated with ecosystem health as it reflects the standing stock of primary producers supporting an ecosystem. Neither elevated chlorophyll-a concentrations or high levels of phytoplankton biomass necessarily indicate degraded water quality or harmed aquatic life, whereas high concentrations of a toxic substance will always indicate degraded water quality and harm. While prevention of harmful algae blooms (i.e., high cell densities of algal species that exhibit toxicity) is certainly one goal of the proposed chlorophyll-a criteria, these criteria do not represent a threshold over which harm is expected, as is the case with toxic substances (typically metals and manufactured organic compounds). Rather, they represent a threshold above which the likelihood of HABs (and other effects) is greater than 10%. Whether adverse effects actually manifest at a high chlorophyll-a concentration depends on the alignment of such variables such as flow, light availability, temperature, wind and circulation patterns, salinity, grazing rates, algal composition, and algal toxin production. Adverse effects are not expected to follow from the majority of small chlorophyll-a exceedances due to the importance of these physical variables. Thus, it should not be assumed that chlorophyll-a criteria exceedances are disastrous enough that they should be prevented from occurring too close in time (e.g., two consecutive seasons), irrespective of exceedance magnitude.

- **The majority of exceedances are predicted to be small.** VADEQ acknowledges that large exceedances of the proposed seasonal mean criteria could be associated with adverse effects. But there are two reasons to expect that most seasonal mean exceedances would be small. First, compliance with the proposed short-duration criteria would put an upper limit on the magnitude of seasonal mean exceedances. For instance, the two short-duration criteria applicable to JMSTFL (a monthly average of 52 µg/l in the upper zone and a monthly average of 42 µg/l in the lower zone) would individually be allowed to be exceeded only once in six years. Given the average temporal variability of chlorophyll-a in the entire JMSTFL segment, 42 µg/l is predicted to be the highest summer mean concentration that JMSTFL can experience in six years while still being compliance with the allowable frequency of its short-duration criteria[13]. This would be considered a large exceedance since the summer mean criterion is 24 µg/l. But since this large exceedance would only be allowed to occur once in six years, it is reasonable to expect that aquatic life would be resilient to the adverse harm incurred by that exceedance. The second reason that VADEQ believes that most seasonal mean exceedances would be small stems from the fact that as site-specific criteria, the proposed seasonal mean criteria are heavily informed by current ambient chlorophyll-a concentrations. Even when the proposed criteria are attained on a long-term basis, ambient concentrations are expected to hover around the proposed criteria. Thus, small exceedances are expected to occur on a regular basis simply due to natural variability. One can reasonably expect these exceedances to be evenly spaced in time (perhaps "once every three years"). But because the natural variability of chlorophyll-a is heavily influenced by weather events that may cluster in time—as is the case with

[13]A summer mean higher than 42 µg/l is likely to be associated with two or more months with excessively high chlorophyll-a concentrations (in the upper zone or lower zone). The proposed short-duration criteria frequency rule would only permit a single "bad" month in six years.

drought years (see Cebrián and Abaurrea, 2006)—it is also reasonable to expect chlorophyll-a criteria exceedances to occasionally cluster.

- **The allowable frequencies of the proposed criteria are protective of aquatic life recovery from the physicochemical effects the proposed criteria are developed to address.** The proposed seasonal mean criteria are developed to protect the tidal James River from multiple physicochemical effects: elevated pH, poor water clarity, and low dissolved oxygen. These effects are already protected by numeric water quality criteria in Virginia's Water Quality Standards (WQS). These numeric criteria have their own exceedance frequencies. pH criteria are allowed to be exceeded 10% of the time over an interval determined useful for assessment purposes (currently six years), as recommended by EPA for conventional parameters (USEPA, 2003a). VADEQ believes that compliance with the proposed chlorophyll-a criteria will ensure that the pH criteria exceedance frequency is upheld regardless of the spacing of the chlorophyll-a criteria exceedances. Furthermore, although pH does become elevated in areas within the tidal fresh and the oligohaline at times when chlorophyll-a is also elevated, excursions above the upper pH criterion of 9.0 tend to be small (no observations of pH greater than 9.5 have been observed) and of low duration (several hours or less). The harm caused by these excursions is unknown, but reduced survivorship is an unlikely effect in the absence of high ammonia concentrations or another toxic stressor. In contrast to pH criteria, the dissolved oxygen criteria and water clarity acreage goals applicable to the tidal James River are assessed over three years (though only the latter have a WQS frequency statement involving three years). DO criteria are limited to either a 10% space-time distribution (30-day and 7-day mean criteria) or 10% temporal exceedance rate (instantaneous minimum criterion) over three years. Since low DO is not a persistent problem in the tidal James River, VADEQ believes that long-term compliance with the proposed chlorophyll-a criteria will keep phytoplankton biomass from increasing to a level where it could begin contributing to persistent hypoxic conditions, assuming that current physical characteristics of the tidal James River hold steady. VADEQ believes this protection will be provided no matter the spacing of proposed criteria exceedances. Water clarity acreage goals are also assessed over three consecutive years (growing seasons), but granted a comparatively more lenient exceedance frequency compared to DO criteria. A waterbody is allowed to not attain a site-specific water clarity goal in two out of three growing seasons. This frequency is justified on the basis of submerged aquatic vegetation resiliency. It is assumed that one good growing season out of three is enough to sustain a SAV bed over the long-term. This assumption is held even though there is speculation that poor water clarity in one growing season can have negative impacts on the growth of SAV in the following season

(Batiuk et al., 2000). Compared to this frequency rule, the allowable exceedance frequencies for the proposed chlorophyll-a criteria are more protective.

- **The allowable frequencies of the proposed criteria are protective of aquatic life recovery from the HAB effects the proposed criteria are developed to prevent.** There are two HAB organisms that are identified as having a high enough prevalence in the James River to warrant concern: the cyanobacteria *Microcystis aeruginosa* in the tidal fresh and the dinoflagellate *Cochlodinium polykrikoides* in the lower estuary. For the former, the proposed criteria were developed to limit concentrations of the toxin the organism produces--microcystin. The James River Chlorophyll-a Study found that the microcystin levels in the tidal James are not high enough to pose a risk to survivorship or reproduction (Vogelbein and Reece, 2013; Bukaveckas et al., 2014), though there is a suggestion that the levels may be high enough to trigger a reduced filtering response in one species of clam (Wood et al., 2016). In lieu of an ecologically relevant microcystin concentration linked to serious harmful aquatic life effects, VADEQ decided to use the WHO-recommended drinking water guidance value of 1 µg/l as an effect threshold. This value is derived from high-dose toxicity studies conducted on mammals and represents a concentration that is considered safe for daily human consumption. The proposed summer mean criteria are developed to prevent microcystin concentrations from exceeding this guidance value more than 10% of the time over the summer season. The proposed short-duration criteria are developed to prevent the duration of elevated microcystin levels from exceeding a single month over a six year period. VADEQ believes compliance with these criteria should prevent potentially harmful levels of bioaccumulation of the toxin in fish and wildlife. Since (1) there are no studies demonstrating that either harmful effects or bioaccumulation are occurring or are likely to occur in the James River due to current microcystin concentrations and (2) chlorophyll-a concentrations can become elevated in the tidal fresh in the absence of toxin-producing cyanobacteria blooms (Egerton and Marshall, 2014), VADEQ believes that there is no basis for assuming two closely spaced exceedances will impede recovery more than exceedances separated by one year or more would.

  In the case of the dinoflagellate *Cochlodinium polykrikoides*, the proposed summer mean criteria and short-duration criteria are developed to limit the incidence rate of cell densities (1,000 cells per ml or greater) associated with mortality to no more than 10% of the time during the summer in the lower estuary (JMSMH and JMSPH). However, exceedances above the proposed criteria indicate "high risk" conditions rather than inhospitable conditions, since chlorophyll-a is a rather imperfect predictor of *C. polykrikoides* densities and the harmful effects caused by C. polykrikoides blooms are modulated by factors such as temperature (Griffith and Gobler, 2016) and wind-driven mixing (Morse et al., 2011). At any rate, VADEQ believes that granting a 10% frequency to this particular effect provides the same level of protection to aquatic life recovery as EPA's recommended 10% exceedance frequency for criteria of conventional parameters like temperature, pH, and dissolved oxygen.

The assumption underpinning a criteria frequency statement is that aquatic life can fully recover as long as adverse effects are temporally spaced out by the minimum specified interval. Stipulating that high exposure events of toxic substances should not be spaced any closer than three years seems reasonably protective, given what is known about the toxicity, fate, and transport of this class of pollutants. This spacing also makes sense for something like hypoxic events, since they tend to be spatially localized and limited in duration; thus, it can be assumed impacted aquatic communities can be restored relatively quickly through recruitment from surrounding areas. But the broad range of estimated recovery periods that have been documented in the context of nutrient pollution—from less than one year to nearly a century (McCrackin et al., 2017)—strongly suggests that a longer recovery period should be assumed in the context of James River chlorophyll-a. As stated above, large exceedances of the seasonal mean criteria would likely be associated with some adverse effects, particularly during the summer when HABs are an issue. But the proposed short-duration criteria constrain the magnitude of summer mean exceedances so that a segment at high risk of harmful effects (i.e., one with documented HABs) would be permitted only one large summer mean exceedance in six years. VADEQ believes this result holds more promise for full aquatic life recovery than what would follow from the adoption of the "one exceedance in three years" frequency rule—which is typically used in ways that do not consider the magnitude of exceedance. While there is not enough information at this point to confidently conclude that the tidal James River needs at least six years to fully recover from severe algal blooms, the weight of evidence gathered in other ecosystems (Borja et al., 2010; McCrackin et al., 2017; Moreno-Mateos et al., 2017) leans more towards this interval than a shorter one.

In summary, the scientific bases of numeric James River chlorophyll-a criteria have been affirmed by the wealth of information generated by the James River Chlorophyll-a Study. Through this study, the Commonwealth has gained a clearer understanding of chlorophyll-a dynamics and its ties to harmful effects on aquatic life. The results of the study underscore the importance of reviewing numeric chlorophyll-a criteria so that policy decisions can track advances in scientific understanding.

CHLOROPHYLL-A CRITERIA ASSESSMENT METHODOLOGY

Description of 2006 Assessment Methodology

Since Virginia's adoption of water quality criteria specific to the Chesapeake Bay and its tidal tributaries in 2006, the Commonwealth has used a procedure for assessing James River chlorophyll-a originally developed by the Chesapeake Bay Program Partnership. This procedure is similar to what is used to assess Bay-wide dissolved oxygen criteria. A series of technical guidance documents (USEPA, 2007, 2008, 2010) present the theory and step-by-step instructions of this approach, which is also described below:

	30			30
1-Jul			50	
	10			10
	10			10
1-Aug			30	
	20			10
	40			20
1-Sep			20	
	10			10

a.

	30	40	50	30
1-Jul	40	40	50	20
	30	30	40	10
	20	30	30	10
	10	20	30	10
1-Aug	20	20	30	20
	10	30	20	10
	10	10	10	10
	40	30	20	20
1-Sep	30	20	20	10
	20	20	10	10
	10	10	10	10

b.

23	29	31	18
29	25	31	16
18	26	20	10
13	14	14	10

c.

X	X	X	X
X	X	X	X
X	X	X	✓
✓	✓	✓	✓

d.

a. Data are collected at sampling locations in a segment (represented as a grid). In this example, the segment has five stations, and the values represent chlorophyll-a samples taken at those stations. James River chlorophyll-a assessments are based on both monthly station visits and spatially intensive "underway" sampling (Dataflow). Three monthly monitoring runs are shown.

b. Data are spatially interpolated to create a segment-wide "snapshot" of chlorophyll-a for each monitoring run. Only surface measurements are interpolated, in accordance with the settings of the Chesapeake Bay Interpolator specified in USEPA (2008). Each monitoring run in the assessment period is represented by a two-dimensional interpolation grid.

c. A composite "seasonal" grid representing the chlorophyll-a expression of a spring or summer season is created by taking the average of the interpolation grids comprising that season. For James River chlorophyll-a, a geometric mean is calculated.

d. The attainment status of each composite grid cell is determined by comparing values against the appropriate criterion. The spatial exceedance rate is determined by dividing the total number of exceedances (i.e., values above the criterion) into the total number of grid cells. In this example, the criterion is 15 µg/L.

Season-Year	Spatial Exceedance Rate
Spring Year 1	31.3%
Spring Year 2	10.0%
Spring Year 3	25.0%

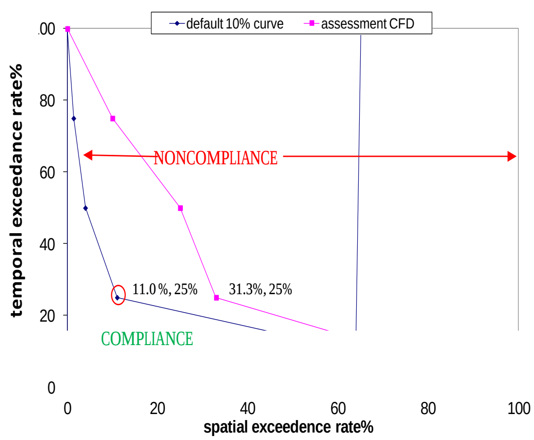
e.

e. The spatial exceedance rate for each season-year of the 3-year assessment period is determined. (So the above steps are repeated on two additional years' worth of data). Then the spatial exceedance rates are ranked from highest to lowest.

Season-Year	Ranked Spatial Exceedance Rate	Temporal Exceedance Rate
	100%	0%
Spring Year 1	31.3%	25%
Spring Year 3	25.0%	50%
Spring Year 2	10.0%	75%
	0.0%	100%

f.

f. A temporal exceedance rate is determined by using the Weibull equation (100*R/n+1) where R = rank and n = sample size (in this case, three).



g.

g. Exceedance rates are plotted against a reference curve as a cumulative frequency distribution (CFD). Virginia uses a 10% hyperbolic reference curve. A segment in compliance displays a CFD which does not cross the reference CFD. Thus, the segment in this example is in noncompliance since it crosses the curve at all three points.

This approach to implementing chlorophyll-a criteria is certainly innovative. The CFD framework was developed to prevent aquatic life from losing "too much" suitable habitat to impairment while simultaneously protecting aquatic life from the impact of "too many" time intervals (days, months, seasons) spent under impairment. The CFD provides a means of defining "too much" and "too many" in a scientifically defensible, systematic way. More conventional assessment procedures usually focus solely on temporal exceedance frequency, since spatial uniformity of attainment in an assessment unit is typically assumed (USEPA, 2005). Because the CFD does not require this assumption to be met, it would seem well-suited for the characterization of the large, complex segments of the Chesapeake Bay and its tidal tributaries.

While certainly qualifying as "state-of-the-art", it is also true that the CFD approach is very experimental. In 2005, the Chesapeake Bay Program's Scientific Technical Advisory Committee (STAC) tasked a workgroup to identify issues related to the CFD's utility as an assessment tool. Among other "critical research tasks", the panel recommended that further research be directed towards developing a better understanding of how well the CFD represents spatial and temporal "covariances of attainment" (STAC, 2006). But with the exception of modified reference curves for Bay-wide dissolved oxygen criteria assessments (USEPA, 2010a) and the incorporation of spatially-intensive datasets (Dataflow) for use in James River chlorophyll-a assessments, the protocol has not changed fundamentally since the STAC report. The biases and uncertainties of the CFD, at least in the context of chlorophyll-a criteria attainment, were largely unknown when the framework was adopted by Virginia.

As a part of the James River Chlorophyll-a Study, VADEQ reviewed the CFD approach in the context of chlorophyll-a criteria assessments. Based on the work of independent consultants, VADEQ identified two problems with this approach:

1. The approach does not lead to accurate attainment determinations when sampling is conducted through a conventional monitoring program (Perry, 2015)[14]. Moreover, the approach appears to be severely biased towards nonattainment when this kind of data is used, which may explain (at least in part) why the criteria are not fully attained at the target nutrient loading scenario of the Bay TMDL (Appendix O., Bay TMDL, 2010b). It appears that the only way to minimize this bias is to employ expensive spatially-intensive monitoring. Budget constraints make this an untenable position for the Commonwealth.

2. There is little scientific basis for allowing only a 10% space-time distribution for chlorophyll-a exceedances in the James (Buchanan, 2014). Although Virginia has a practice of applying a "10% rule" to water quality samples when determining compliance for conventional pollutants, this is typically only done when assessing instantaneous criteria, not criteria expressed as a seasonal average. Although the 10% reference curve is very stringent (and thus theoretically very protective), it is unknown whether forcing the distribution of James River chlorophyll-a to resemble the 10% reference curve would actually be beneficial to aquatic life. The framework suffers from a defensibility problem as long as it is laden with untested/untestable assumptions.

Recommended Assessment Method

The highly variable nature of pollutants and response parameters in both space and time complicates the implementation of water quality criteria. Assessment methodologies are developed with pollutant variability in mind, but only rarely are they are tailored to the nature of individual pollutants in specific waterbodies. This would be ideal, since variability informs

[14] Perry (2015) only analyzed chlorophyll-a, not other water quality parameters such as dissolved oxygen. It is highly unlikely that dissolved oxygen assessments are complicated by uncertainty to the same degree that chlorophyll-a assessments are. Chlorophyll-a is a parameter that is not freely dissolved in water but rather contained in organisms with clumped patterns of dispersion. This "patchiness" is not expected with a dissolved substance. Thus, the problems identified by Perry should not be generalized to dissolved oxygen criteria assessments.

the certainty of assessment results. Methodology which does not fully account for pollutant variability can lead to the under- or overestimation of water quality criteria exceedances. EPA (2001) recommends a number of sampling strategies and data analyses for addressing variability in nutrient indicators like chlorophyll-a in estuaries and coastal waters.

VADEQ believes that the current assessment method and decision rules for James River chlorophyll-a do not appreciate the inherent "patchiness" and "flashiness" nature of this indicator. Thus, the agency proposes to move away from the CFD framework. Rather than predicating criteria attainment upon the distribution of spatial-temporal exceedance rates—for which a threshold linked to aquatic life impacts has yet to be determined empirically—the replacement method would be based on a more literal interpretation of the water quality standard. Data would be spatially averaged over a segment for each monitoring run and temporally averaged over a season—resulting in a single value to be directly compared to the appropriate criterion. This method has the advantage of being easier to implement than the CFD framework. But more importantly, unlike the relationship between the 2006 methodology and 2005 chlorophyll-a criteria, the recommended methodology would be fully consistent with the derivation of the recommended criteria.

Recommended Data Analysis Procedure

1. For each cruise in a segment or (where applicable, segment-zone), observations of chlorophyll-a taken at different locations shall be averaged together. A median is recommended since this is the best measure of central tendency when the distribution of a sample population is not always known. Although most spatial datasets indicate that James River chlorophyll-a exhibits a lognormal distribution (thereby justifying the use of a geometric mean), a median is a "safe" statistic widely used in water quality reporting.
2. For each month-year of the spring and summer seasons, the median of monitoring run median values shall be calculated. A median is recommended based on the same reasoning provided above. Aggregating by month smooths out any biases that may arise if monitoring datasets have uneven temporal spacing (e.g., weekly samples in March with monthly samples in April and May).
3. For each season-year of a segment or segment-zone, a geometric mean of month-year median values shall be calculated.
4. The following equations shall be used to calculate the segment-wide seasonal geometric mean (GM) of JMSTFU and JMSTFL (see Appendix A for the technical basis):

JMSTFU seasonal GM = upstream zone seasonal GM * 0.41 + downstream zone seasonal GM * 0.59

JMSTFL seasonal GM = upstream zone seasonal GM* 0.49 + downstream zone seasonal GM * 0.51

5. Seasonal geometric means (rounded to the nearest whole number) shall be compared to the appropriate segment-season criterion.
6. The median of same-day samples (rounded to the nearest whole number) shall be calculated to assess criteria having a 1-day duration, and the median of same-day medians (rounded to the nearest whole number) within the same month shall be calculated to assess criteria with a 1-month duration.

Recommended Decision Rules for Non-Attainment

1. A six-year assessment period shall be used.
2. A segment shall be determined to be in non-compliance if either of its seasonal mean criterion is exceeded more than twice or (where applicable) the short-duration criteria are exceeded more than 10% of the time.

Recommended Approach for Spatially Intensive Datasets

Though VADEQ anticipates that the EPA-Chesapeake Bay Program Office-funded fixed station network will continue to be the primary source of data for much of the estuary, it also believes that the characterization of chlorophyll-a is significantly enhanced when datasets such as Dataflow are brought into the analysis. The recommended assessment method would be fully compatible with this type of monitoring data. These data would be processed before being analyzed, as is the current practice. But VADEQ recommends doing this is a manner that 1) incorporates more spatial variability into chlorophyll-a estimates while 2) reducing uncertainty.

Incorporation of more spatial variability

Dataflow observations would be spatially aggregated by cruise and within zone (JMSTFU and JMSTL only). Aggregated estimates, rather than individual Dataflow observations, are to be used so as to smooth out the effect of any biased monitoring that may occur while the vessel is underway, such as when the vessel slows down to bring bloom samples shipboard.

The current interpolation procedure, as described in USEPA (2008), takes the average (weighted inversely by distance) of the four observations closest to each Interpolator centroid. This means that the great majority of observations taken on a Dataflow cruise are ignored and the full range of chlorophyll-a's spatial variability is underappreciated.

The recommended procedure would require that all observations taken within a grid cell (see Figure 7) be averaged (median), rather than only a small subset. The grid used for processing spatially intensive data points would be similar to the Bay Interpolator grid.

Reducing uncertainty

Currently, data are interpolated throughout the full extent of a segment, even in areas greater than a kilometer away from where samples were actually taken. Patchiness can occur even in relatively homogenous segments. Thus, overly aggressive interpolation introduces avoidable measurement error. The proposed procedure would limit the generation of estimates to only those cells containing at least one observation.[15]

Recommendations for Monitoring

Minimum Data Requirements

In its critical review of the current assessment framework, VADEQ (2016b) cites the examination performed by Perry (2015) which strongly suggests that at least in the case of JMSPH, the framework leads to inaccurate decision-making more often than not when implemented with fixed station datasets. VADEQ views this as a substantial weakness, since the agency's current level of funding and manpower can only support fixed station datasets. While the alternative assessment framework being proposed by VADEQ can be supported through conventional monitoring, it is only prudent that the agency determine whether its current monitoring program is generating datasets that are sufficient to produce confident assessment results.

There are a number of ways an assessment program can determine data "sufficiency". The most conventional way is through a power analysis, a statistical method that uses the variability in a sample population to estimate how many observations are needed to detect an effect in that sample population, given a specified level of confidence. But a power analysis is typically employed when a sampling design has not been established. VADEQ has been using a 30+ years-old sampling design—one that it intends to maintain since it enables the analysis of long-term trends. It is important for VADEQ to determine both how well this design is working and specifically how it can be enhanced given limited resources. So, the power analysis is supplemented with additional analyses using simulated datasets created from spatially/temporally intensive monitoring datasets, the results of which are evaluated in terms of measures of performance.

Power Analysis

Using the mean of the backtransformed mean standard deviations presented in Table 6 and 7 for each segment, the minimum sample sizes needed to generate central tendency estimates

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[15] This recommendation anticipates monitoring designs that are more spatially intensive than the conventional fixed station monitoring network but less intensive than a full Dataflow cruise. As fluorescence sensors become less expensive, it may be feasible to implement a "Dataflow-lite" program—where measurements are taken at regular intervals along a single, mid-channel transect. With such a design, interpolating the chlorophyll-a values shoreline-to-shoreline (as is done with the 2006 methodology) would not be appropriate.

within 10%, 20%, or 30% of the true central tendency were determined for each segment. A statistical power of 85% was selected as the "tolerable" false negative error rate (e.g., for fifteen out of every 100 assessments, a decision of "attainment" will be made when the segment is in non-attainment). The tolerable false positive error rate (alpha) was assumed to be 15% (e.g., for fifteen out of every 100 assessments, a decision of "non-attainment" will be made when the segment is in attainment). As shown in Table 12, according to this analysis neither VADEQ's current complement of stations per segment or its current monitoring frequency are adequate to produce highly confident assessments.

Table 12. Number of samples needed in space and time to produce detect one-sided differences of various magnitudes (10%, 20%, and 30%) between segment central tendency and criteria. CV = coefficient of variation = mean geometric standard deviation divided by the lowest criterion recommended for each segment (see Table 11).

Number of Stations Per Segment	CV	10%	20%	30%	Current Monitoring Design
JMSTFU	0.21	22	7	4	3
JMSTFL	0.14	10	4	3	3
JMSOH	0.14	10	4	3	2
JMSMH	0.28	36	11	5	2
JMSPH	0.21	22	7	4	2
Number of Cruises Per Season	**CV**	**10%**	**20%**	**30%**	**Current Monitoring Design**
JMSTFU	0.21	22	7	4	3
JMSTFL	0.15	12	4	3	3
JMSOH	0.13	10	3	2	3
JMSMH	0.33	50	14	7	3
JMSPH	0.26	32	10	5	3

Simulated Spatial Datasets

Currently, each segment of the tidal James River is monitored on a monthly basis at two or three mid-channel fixed stations. This monitoring is funded by the EPA-Chesapeake Bay Program Office (CBP), and the data collected at these locations supports both chlorophyll-a and dissolved oxygen assessments (as well as the Bay Program's status and trend analysis). VADEQ-funded sampling, as well as discrete samples and Dataflow data provided by Hampton Roads Sanitation District (HRSD), supplement the Bay Program fixed station datasets.

An analysis was performed on existing monitoring datasets to determine the capability of the current CBP-funded station network (CBP) to capture the variability of chlorophyll-a at the sensitivity needed to render a confident assessment decision using the recommended procedure. For the two tidal fresh segments and JMSOH, all available Dataflow cruises were analyzed (n = 19 to 55). For JMSMH and JMSPH, 50 and 44 cruises were selected, respectively.

The Dataflow datasets were processed in accordance with the recommended procedure. The spatial central tendency of chlorophyll-a was calculated for each cruise in multiple ways:

1. The Dataflow median: the median of all grid cell values, factored by area-derived weights when appropriate.
2. The CBP median: the median of values associated with the grid cells coinciding with the CBP stations, factored by area-derived weights when appropriate.
3. The CBP+X median: the median of values associated with the grid cells coinciding with the CBP stations and an additional station X, factored by area-derived weights when appropriate.
4. The CBP+X+Y median: the median of values associated with the grid cells coinciding with the CBP stations and additional stations X and Y, factored by area-derived weights when appropriate.
5. The CBP+X+Y+Z median: the median of values associated with the grid cells coinciding with the CBP stations and additional stations X, Y, and Z, factored by area-derived weights when appropriate. Figure 16 shows the location of the CBP and additional stations.

For each segment, 50 unique triads of the aforementioned cruise datasets—each cruise representing a different "monthly" monitoring run—were used to generate simulated seasonal central tendencies of chlorophyll-a. For each simulated season, a geometric mean of the three Dataflow-derived medians was calculated. This mean was treated as the true chlorophyll-a expression for that "season". The medians produced by the different fixed station designs were averaged in a similar manner and were treated as *estimates* of the true chlorophyll-a expression.

To determine how well the different fixed station designs capture the "true" spatial-temporal central tendency of chlorophyll-a, two different evaluations were made:

1. Mean absolute difference: For each simulated season, the absolute difference between the full Dataflow mean and the mean enabled by a particular fixed station design was calculated. The mean absolute difference is the average of all the absolute differences over all the simulated seasons for each fixed station design. A fixed station design enabling a mean absolute difference less than or equal to 2 µg/L is considered acceptable[16].

[16] An absolute difference is not a perfect measure of performance . It is reasonable to argue that a design that produces an estimate of 18 µg/L when the "true" value is 20 µg/L is superior to a design that produces an estimate of 1 µg/L when the "true" value is 3 µg/L. But in this context (environmental sampling), it is unreasonable to conclude that the latter is an abject failure simply because it has a much higher percent error (60% versus 10%). Since percent error grows larger the smaller the "true" value is and most of the "true" chlorophyll values in this analysis were small (less than 10 µg/L), an absolute difference was used for communicating performance.

2. Assessment error rate: the rate of "false negatives" and "false positives" produced by the fixed station designs. For the former examination, it is assumed that the segment is always in noncompliance of a criterion that is equal to whatever the Dataflow seasonal mean is minus 2 µg/L. So, if a fixed station design generates a seasonal mean that is less than this value, the assessment outcome is deemed a "false negative" (a decision of attainment is made when the true state is non-attainment). For the latter examination, it is assumed that the segment is always in compliance of a criterion that is equal to whatever the Dataflow seasonal mean is plus 2 µg/L. So, if a fixed station design generates a seasonal mean that is greater than this value, the assessment outcome is deemed a "false positive" (a decision of non-attainment is made when the state is attainment).

As shown in Figures 16, the ability of the current sampling network ("CBP") to capture the central tendency of chlorophyll-a varies by segment. It is evident that the tidal fresh segments are not adequately covered by the current set of stations. Not only does it appear that the stations are too limited in coverage to enable good estimates of central tendency, but it also appears that sampling at these locations results in highly biased assessment outcomes—a skew towards attainment for JMSTFU and one towards non-attainment for JMSTFL. However, the addition of a single station to each the two segments' current complement would likely reduce errors to an acceptable level. Interestingly, it appears that the remaining segments are adequately served by their current stations—even the very large mesohaline segment. The explanation for this is apparent with closer inspection of the data. When cruise datasets are assessed individually, the CBP stations in JMSMH tend to produce estimates with low accuracy—characterized by an average absolute difference of 4 ± 2 µg/L and an assessment error rate of 36%. But these errors are washed out when cruise datasets are averaged to create "seasonal" composites. This suggests that while the two CBP stations in JMSMH may be adequate for assessing a seasonal mean criterion, they would not be enough for assessing a 90^{th} percentile or instantaneous maximum criterion—whereby non-compliance is predicated on data that are not "smoothed" by temporal averaging.

In most cases, it appears that fixed station datasets tend to overestimate chlorophyll-a concentrations. While not ideal, it would be more concerning from an aquatic life protection stand-point if these datasets were more likely to produce "false negatives". The bias is not as severe as the bias documented by Perry (2015) in relation to the CFD framework.

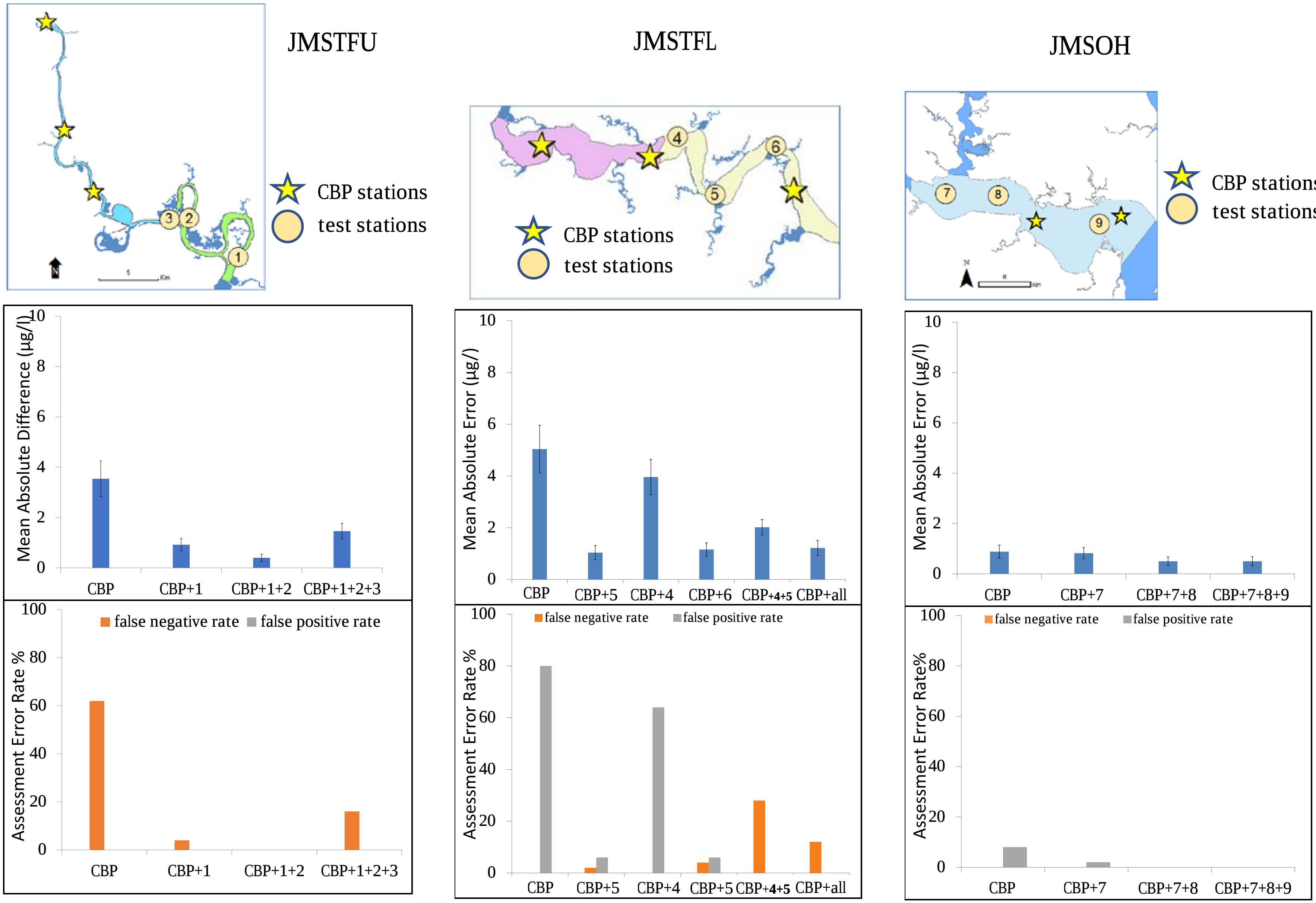

Figure 16. Mean absolute difference between the full Dataflow estimate of spatial central tendency and the estimates generated by the different fixed station designs. Error bars show 95% confidence interval. Bottom: Error rate of the assessment outcomes generated by the different fixed station designs.

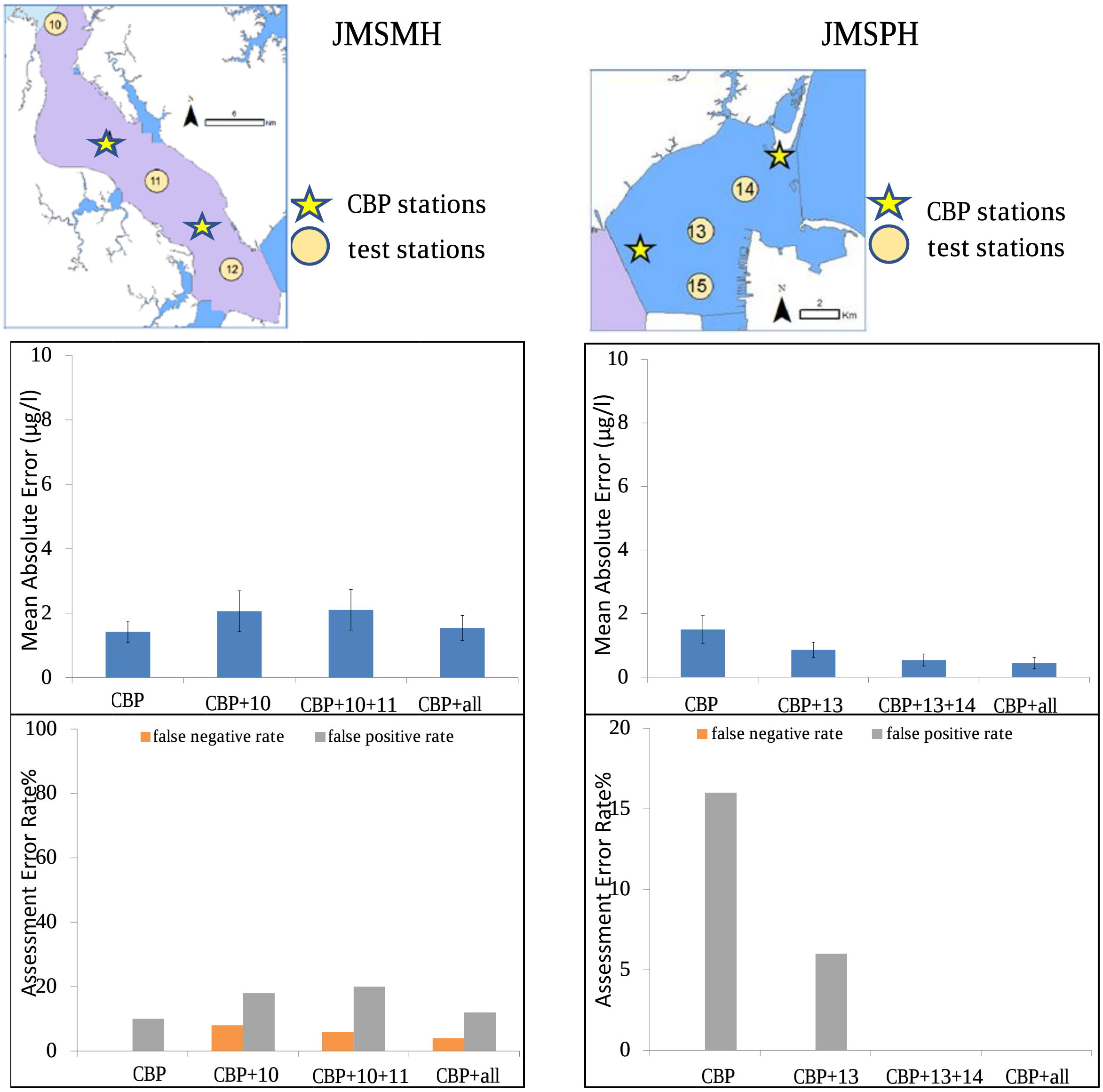

Figure 16 (cont). Mean absolute difference between the full Dataflow estimate of spatial central tendency and the estimates generated by the different fixed station designs. Error bars show 95% confidence interval. Bottom: Error rate of the assessment outcomes generated by the different fixed station designs.

Simulated Temporal Datasets

The previous examination was more of a performance test in the spatial dimension rather than a performance test of the current monitoring design's ability to capture temporal central tendency. To accomplish the latter, the chlorophyll-a means for summer 2006, 2007, and 2008 were calculated using continuous monitoring (ConMon) datasets in the following three ways:

1. A geometric mean of all valid observations taken by the ConMon during a summer-year. This value represents the "true" seasonal central tendency of chlorophyll-a in the segment.
2. A geometric mean of three observations separated by a month, collected at the same time of day, in a summer-year. Two times of day were selected: 7:00AM and 12:00PM. All possible n=3 combinations were analyzed to maximize sample size.
3. A geometric mean of six observations separated by 14 days, collected on the same time of day, in a summer-year. Two times of day were selected: 7:00AM and 12:00PM. All possible n=6 combinations were analyzed to maximize sample size.

The absolute difference between the full ConMon mean and each estimate was calculated, and then the mean absolute difference was calculated by taking the average of all absolute differences for each sampling frequency design. The rates of false negatives and false positives were also calculated for the two sets of estimates, using the same criteria rubric employed in the previous analysis.

As shown in Table 13, the seasonal central tendency of chlorophyll-a is poorly captured by monthly sampling in two segments—JMSTFL and JMSMH. (JMSPH is considered a "borderline" case). It is evident that the temporal dynamics in these segments are such that more frequent monitoring is needed to render good estimates of seasonal central tendency. The mean seasonal standard deviations calculated for JMSTFU and JMSTFL might cause one to surmise that the former would be more likely to require more frequent sampling than the latter, but the opposite appears to be the case. It could be that there is less consistency in the temporal

Table 13. Performance of monthly and semi-monthly chlorophyll-a sampling for each segment. n = number of trials.

	Monthly				Semi-Monthly			
	Mean Absolute Difference (µg/l)	False Negative Rate%	False Positive Rate%	n	Mean Absolute Difference (µg/l)	False Negative Rate%	False Positive Rate%	n
JMSTFU	1.9 ± 0.3	17%	8%	158	1.8 ± 0.2	6%	1%	69
JMSTFL	3.0 ± 0.5	27%	22%	60	2.2 ± 0.7	17%	11%	18
JMSOH	1.5 ± 0.2	11%	8%	148	1.3 ± 0.2	7%	7%	60
JMSMH	2.9 ± 0.3	35%	18%	130	2.4 ± 0.4	30%	13%	56
JMSPH	2.2 ± 0.3	16%	16%	147	1.6 ± 0.4	15%	10%	59

variation of JMSTFL's chlorophyll-a expression than in that of JMSTFU, even though the latter appears to exhibit greater overall variability. Fortunately, weekly monitoring datasets have been collected in both JMSMH and JMSPH by the Hampton Roads Sanitation District for more than ten years, and VADEQ will continue to use these datasets as long as they continue to be available. In the case of JMSTFL, the results of the analysis indicate that monitoring runs spaced out by two weeks should be sufficient for producing confident assessments. This level of commitment may be difficult for VADEQ to maintain, but datasets generated by other data collectors (university researchers, local governments, and non-governmental organizations) could be used to reduce uncertainty.

The following summarizes the recommended modifications in VADEQ's monitoring design for James River chlorophyll-a based on all the above performance tests:

1. At a bare minimum, additional fixed stations are needed in JMSTFU and JMSTFL. The current stations are located in areas that are not representative of overall chlorophyll-a expression.
2. VADEQ should continue soliciting and using data from other data collectors, especially for the sake of the lower estuary, where monthly fixed station monitoring appears to be inadequate. Non-VADEQ monitoring events that intersperse VADEQ monitoring events would enable sample sizes sufficient for robust characterization of seasonal chlorophyll-a expression.
3. In the absence of full-scale Dataflow monitoring, VADEQ should consider measuring chlorophyll-a in-situ (via fluorescence sensor) while conducting routine fixed station monitoring. While it would be very difficult for VADEQ to mobilize the resources needed for weekly monitoring runs, improving the accuracy of monitoring event characterizations is a much more reachable goal with the available technology.
4. When resources allow, either nearshore or mid-channel continuous monitors should be deployed. An assessment procedure has not been developed yet for continuous datasets in the context of chlorophyll-a. But while one is being developed, these datasets could be used to verify seasonal means derived from low-frequency sampling.

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APPENDICES

Appendix A. Chlorophyll-a Non-Uniformity in the Tidal Fresh Segments

USEPA (2005) provides guidance on partitioning waterbodies for assessment purposes. States are advised to subdivide complex waters into discrete assessment units (segments) to maintain homogeneity in physical, biological or chemical conditions. A number of factors are to be considered before setting boundaries, such as the expected natural variability of the pollutant/indicator of concern, changes in residence time, land use influences, and channel morphology. Segments are always larger than an individual sampling location, but should be small enough to represent a relatively homogenous parcel of water. The ability to accurately characterize a system using a small number of samples diminishes when segments are not homogenous. Thus, partitioning maximizes the efficiency of a monitoring program.

The boundaries of the Chesapeake Bay segments correspond roughly to salinity regimes, with little consideration given to the factors listed above. Currently, all monitoring stations in a segment are treated as if they are equally representative of that segment's condition. If this assumption is indeed true, aggregating data generated at these locations does not pose a problem. Samples taken at different locations during the same monitoring event would essentially be replicate measurements. But if a particular Bay segment is relatively uniform with regard to salinity while consistently non-uniform with respect to another variable—one that can also affect the pollutant of concern—then it cannot be assumed that the same parcel of water is being sampled at different locations. Indiscriminate averaging of monitoring data could create a false impression of the overall condition of that segment. Moreover, a sampling design that fails to appreciate a segment's non-uniformity can result in uneven protection of designated use(s).

VADEQ believes it is important to test the assumption of segment homogeneity before embarking on any proposed assessment procedure revisions. The agency has no intention of altering the Bay segmentation scheme given the policy complications this would pose. Rather, VADEQ wants to ensure that the assessment procedure it employs for chlorophyll-a criteria assessments accounts for variability better than the current procedure does. VADEQ analyzed two types of monitoring data—discrete samples collected at Dataflow verification stations and interpolated Dataflow cruise data—to examine whether segments should be subdivided.

Analysis of Segment Uniformity

Verification Stations

Verification stations are sites where water samples are collected during Dataflow runs. The chlorophyll-a pigment is extracted from these samples in the laboratory and quantified analytically, thereby allowing in-situ fluorescence measurements to be translated into chlorophyll-a equivalents. Since each

James River segment has at least four verification stations (see Figure A-1), the datasets produced at these stations enable an examination of segment uniformity. If algal biomass is more or less uniform in a segment, one would expect the chlorophyll-a values observed at all the verification stations to be statistically similar.

Spring and summer chlorophyll-a values observed at verification stations in each segment were analyzed over the years 2006-2008 (JMSTFU, JMSTFL, and JMSOH) and 2010-2013 (JMSMH and JMSPH) (shown in Figure A-1). Distributions were compared using a Kruskal-Wallis test followed by a pairwise Wilcoxon Rank Sum test ($p<0.05$). Non-uniformity is evident in the two tidal fresh segments and JMSMH.

However, these results do not allow us to determine if or how these segments should be sub-divided. Most obviously, the fact that the verification stations are widely and unevenly spaced prevents the discernment of natural breakpoints. For instance, if we decide that JMSTFU station JMS082.49 represents a different habitat from the one represented by JMS094.45, how do we determine where one habitat ends and the other begins? Given the lack of water quality information between these stations, the boundary would have to be set according to shoreline features that may be unrelated to spatial patterns in algae growth. It is also important to consider the importance of meaningful difference versus statistical difference. Although lower chlorophyll-a values are observed more frequently at the two upstream stations in JMSMH compared to the more downstream stations, the difference in the "upstream" and "downstream" medians is relatively small—3 µg/L—and thus subdivision of the entire JMSMH habitat may not be warranted.

Dataflow

For each segment, at least six Dataflow cruises were examined to determine the degree of spatial uniformity in chlorophyll-a. A Dataflow dataset was selected for analysis if at least 1% of the observations indicated the presence of algal blooms—defined as chlorophyll-a concentrations greater than 25 µg/L (TF and OH segments) or 15 µg/L (MH and PH). Each dataset was interpolated via kriging. Chlorophyll-a estimates were generated for the same set of point locations used by the Bay Interpolator (restricted to the mainstem). Only "bloom cruises" were analyzed since one would expect non-uniformity in chlorophyll-a distribution to be more apparent when chlorophyll-a concentrations are significantly elevated. There were fewer bloom cruises available for the upper estuary because there were fewer Dataflow monitoring runs conducted there compared to the lower estuary. The excluded cruises that were *not* analyzed in JMSTFU and JMSTL lacked a sufficient number of "bloom" observations. For each segment, the chlorophyll-a estimates from each cruise were compiled into a flat file, with each cruise treated as a different variable. This file was run through a grouping analysis program (ArcMap version 10.1, Environmental Systems Research Institute) which uses the average spatial variance over multiple variables to form groupings. Chlorophyll-a concentrations clustered most strongly into two groups for all segments except JMSOH. Three groups were suggested for this segment, as shown in Figure A-2.

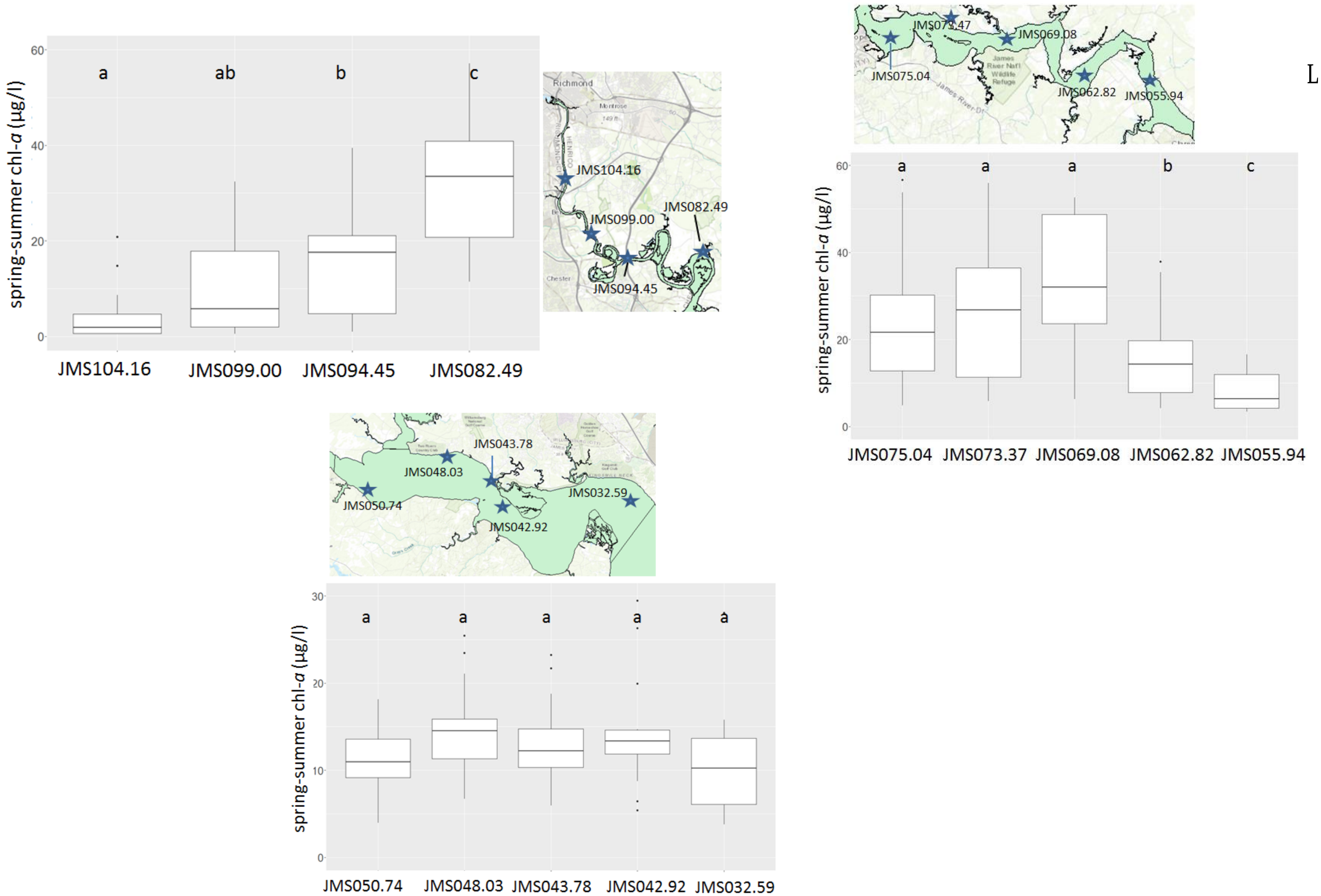


Figure A-1. Chlorophyll-a concentrations observed at stations monitored by VIMS during the spring and summer months 2006 to 2008. The average sample size is 17. Letters indicate statistically similar groups (pairwise Wilcoxon Rank Sum Test, p<0.05).

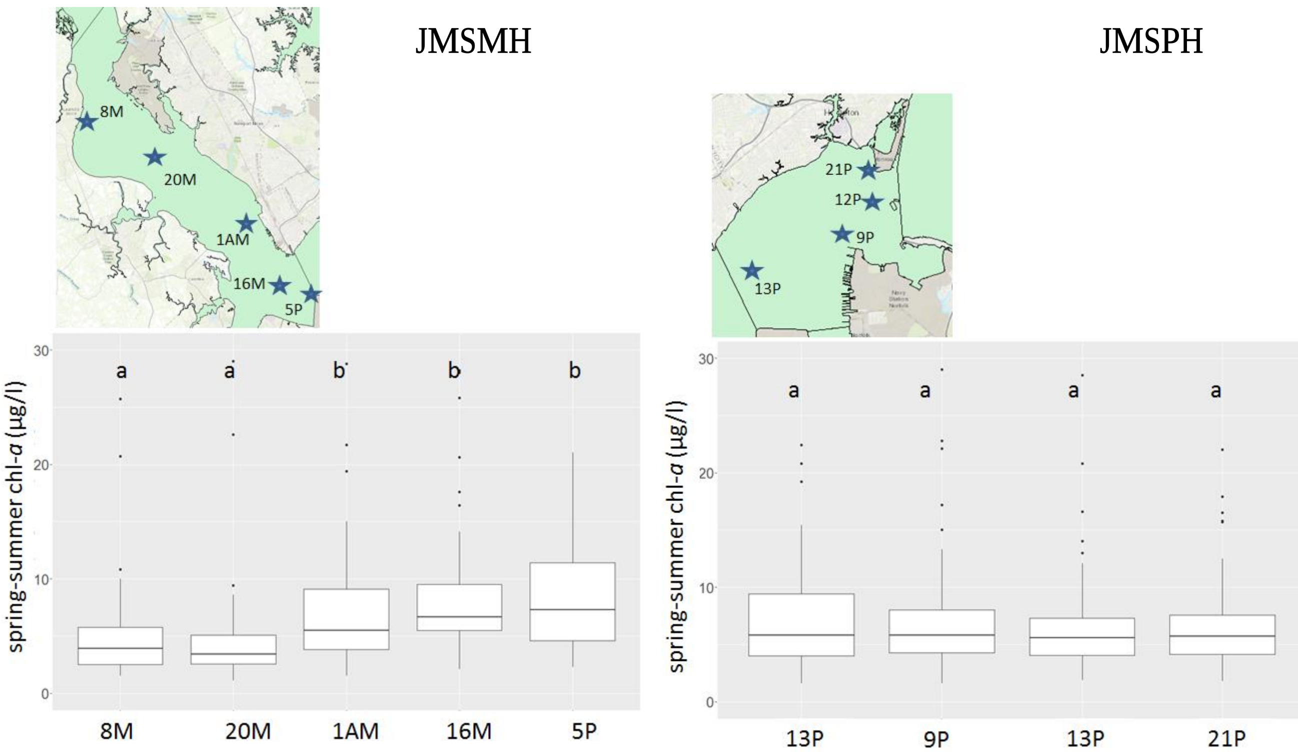


Figure A-1 (cont). Chlorophyll-a concentrations observed at stations monitored by VIMS during the spring and summer months 2006 to 2008. The average sample size is 78. Letters indicate statistically similar groups (pairwise Wilcoxon Rank Sum Test, p<0.05).

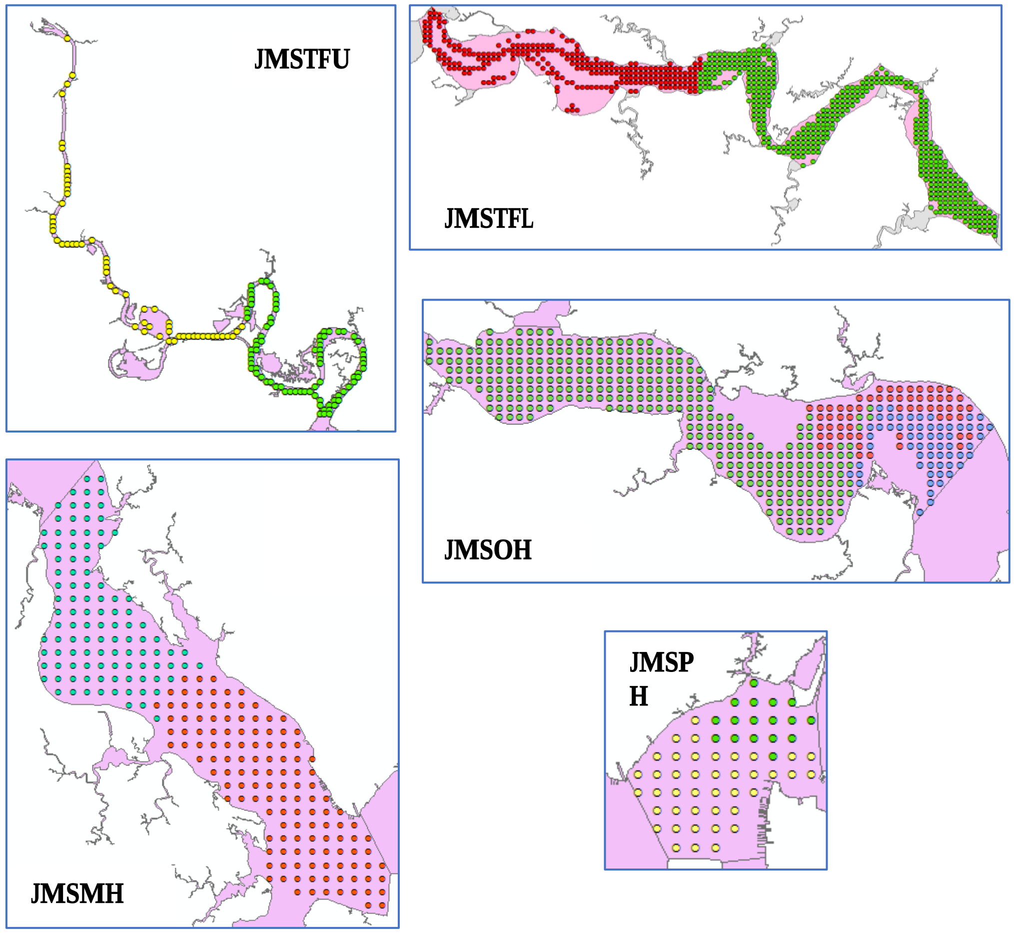


Figure A-2. Suggested within-segment groupings based on the average variance structure of chlorophyll-a observed during "bloom condition" Dataflow monitoring runs. The Calinski-Harabasz *pseudo F-statistic* was used to determine the ideal number of groupings within each segment.

Table A. Grouping statistics for each cruise by segment.

JMSTFU			JMSTFL			JMSOH			JMSMH			JMSPH		
cruise date	R^2	percent difference between group medians	cruise date	R^2	percent difference between group medians	cruise date	R^2	median percent difference between group medians	cruise date	R^2	percent difference between group medians	cruise date	R^2	percent difference between group medians
7/27/2006	0.60	117	7/26/2006	0.57	103	3/28/2006	0.42	142	3/6/2006	0.02	11	8/6/2009	0.14	72
8/24/2006	0.77	94	5/23/2007	0.82	104	8/20/2007	0.29	63	3/8/2006	0.20	131	3/18/2010	0.19	29
4/26/2007	0.56	167	7/25/2007	0.77	126	8/11/2008	0.01	8	8/14/2007	0.01	12	4/22/2010	0.51	29
5/24/2007	0.70	179	8/22/2007	0.89	108	8/20/2012	0.56	66	8/22/2007	0.09	42	8/4/2010	0.01	6
7/26/2007	0.71	100	9/19/2007	0.70	126	3/5/2013	0.42	95	3/10/2008	0.08	11	8/24/2011	0.05	27
9/22/2007	0.77	79	7/1/2008	0.75	109	7/11/2013	0.49	22	7/7/2009	0.17	52	3/15/2012	0.42	27
7/2/2008	0.72	120	8/13/2008	0.89	89				7/12/2010	0.09	40	3/19/2012	0.14	17
8/14/2008	0.78	97							4/25/2011	0.13	45	7/18/2012	0.16	81
									4/6/2011	0.29	86	7/25/2012	0.02	19
									3/7/2012	0.16	92	7/31/2012	0.01	20
									7/17/2012	0.17	95	8/17/2012	0.05	25
									7/23/2012	0.11	51	3/13/2013	0.12	37
									8/1/2012	0.34	152	4/3/2013	0.12	35
									8/12/2013	0.18	97	8/28/2013	0.31	81
									8/19/2013	0.00	12	9/4/2013	0.24	71
median	**0.72**	**109**		**0.77**	**108**		**0.42**	**65**		**0.09**	**40**		**0.14**	**27**

While groupings were created for each segment, not all groupings were deemed *meaningful*. Two factors were used to determine whether the clustering in a particular segment is consistent and pronounced enough to be of concern for assessment. First, the clustering was deemed consistent if the average pseudo-R^2 of all the analyzed cruise data was at least 0.60. A cruise displaying a high R^2 had an observed variance structure that corresponded closely to the grouping suggested by the full model shown in Figure A-2. Secondly, for the majority of the "high R^2" cruises, the percent difference between group medians was at least 100%. It is assumed that a difference of this magnitude would likely lead to inaccurate assessment results if the assessment methodology (including sampling design) does not account for non-uniformity, irrespective of the criteria used to determine attainment. Using the aforementioned criteria, the only segments determined to have a consistent pattern of *meaningful* non-uniformity were the upper and lower tidal fresh segments (see results shown in Table A). This is not a surprising result, since these two segments feature more prominent channel heterogeneity compared to the other segments. It appears that chlorophyll-a tends to concentrate in stretches with reduced velocities (Isenberg, 2012) and, at least in the case of JMSTFL, shallower depth (NOAA, 1998; see Figure A-3) relative to adjacent stretches.

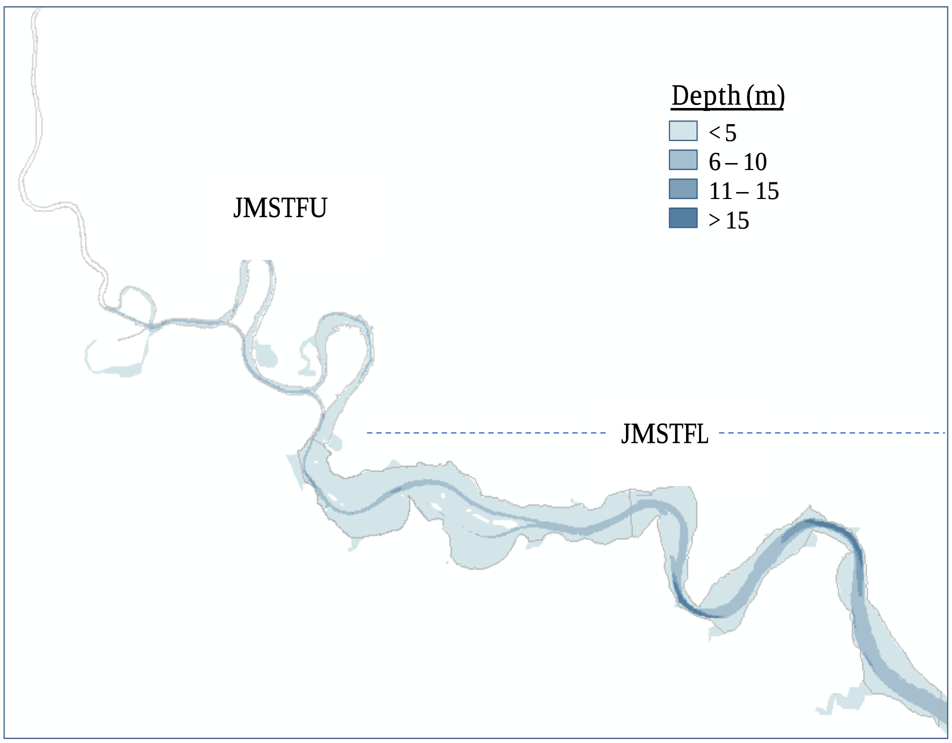
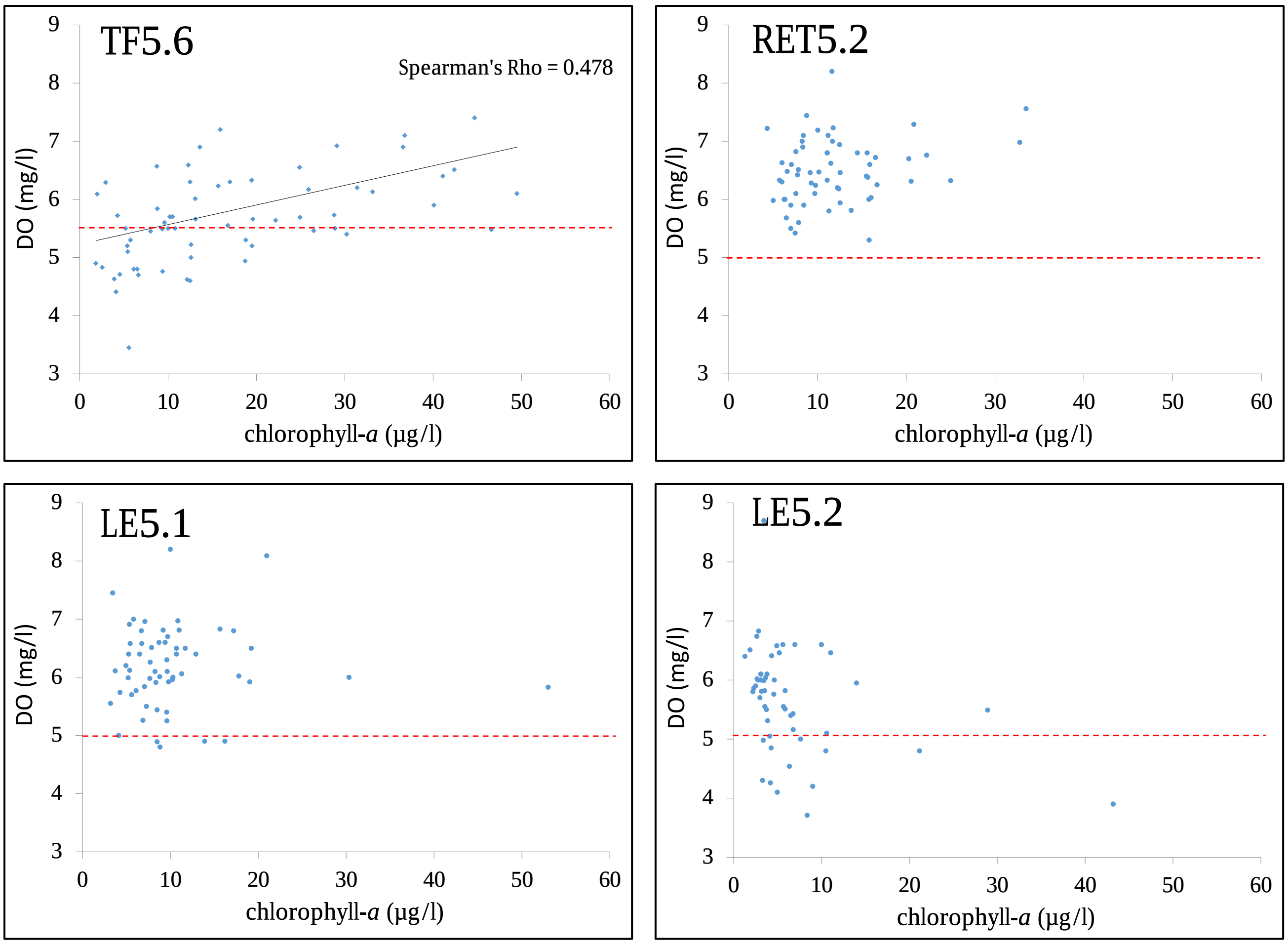


Figure A-3. Bathymetry for the tidal fresh James, based on National Ocean Service survey data (NOAA, 1998). The upstream zone of JMSTFL has a mean and median depth of 4 meters and a maximum of 14 meters. The downstream zone has a mean and median depth of 8 and 6 meters, respectively, and a maximum of 28 meters. Higher hydrologic retention would be expected in the upstream zone relative to the downstream zone due to the former's lower gradient and shallower depth. Bathymetry information is incomplete for JMSTFU.

Appendix B. Additional Chlorophyll-a and DO Visualizations



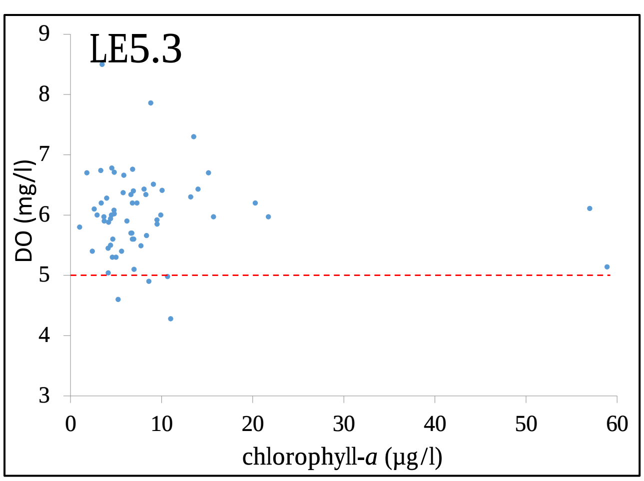
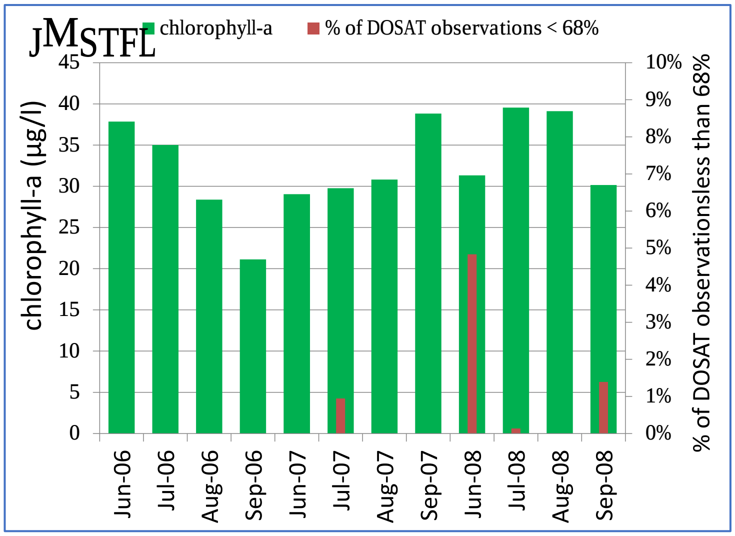
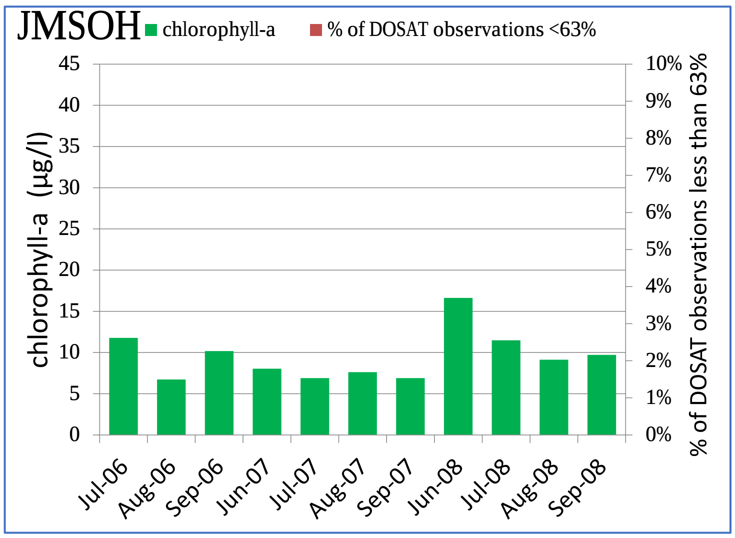


Figure B-1. Scatterplot of summertime DO concentrations versus summertime chlorophyll-a concentrations monitored monthly at selected mid-channel stations during the 1991-2015 period. The red line corresponds to the 30-Day Mean DO criterion (5.0 or 5.5 mg/l) that applies to the segment where the station is located. Trendline indicates a statistically significant correlation ($p < 0.05$).





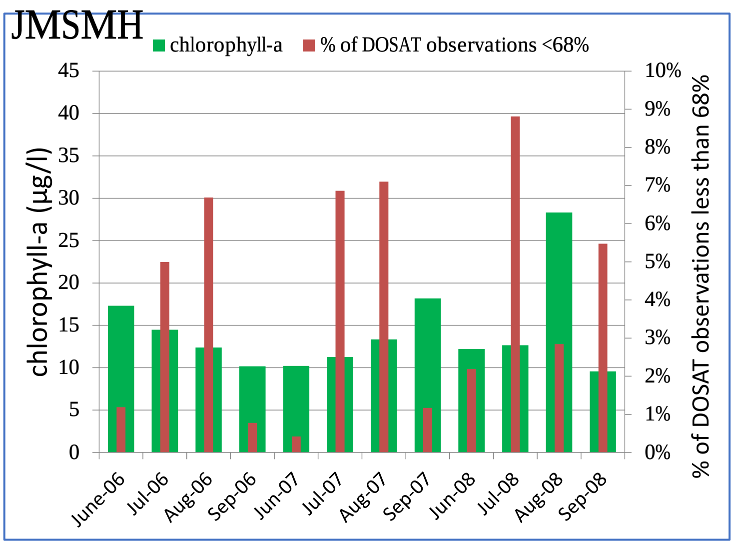


Figure B-2. Monthly summertime chlorophyll-a concentrations (medians) versus the percentage of DO percent saturation observations less than a specified threshold recorded at ConMon stations in JMSTFL, JMSOH, and JMSMH. The DOSAT thresholds correspond to the applicable 30-Day Mean DO criterion (5.5 mg/l or 5.0 mg/), average summertime temperature (26˚C), and the average salinity recorded by the monitor.

Appendix C. Comparison of Published Optical Models

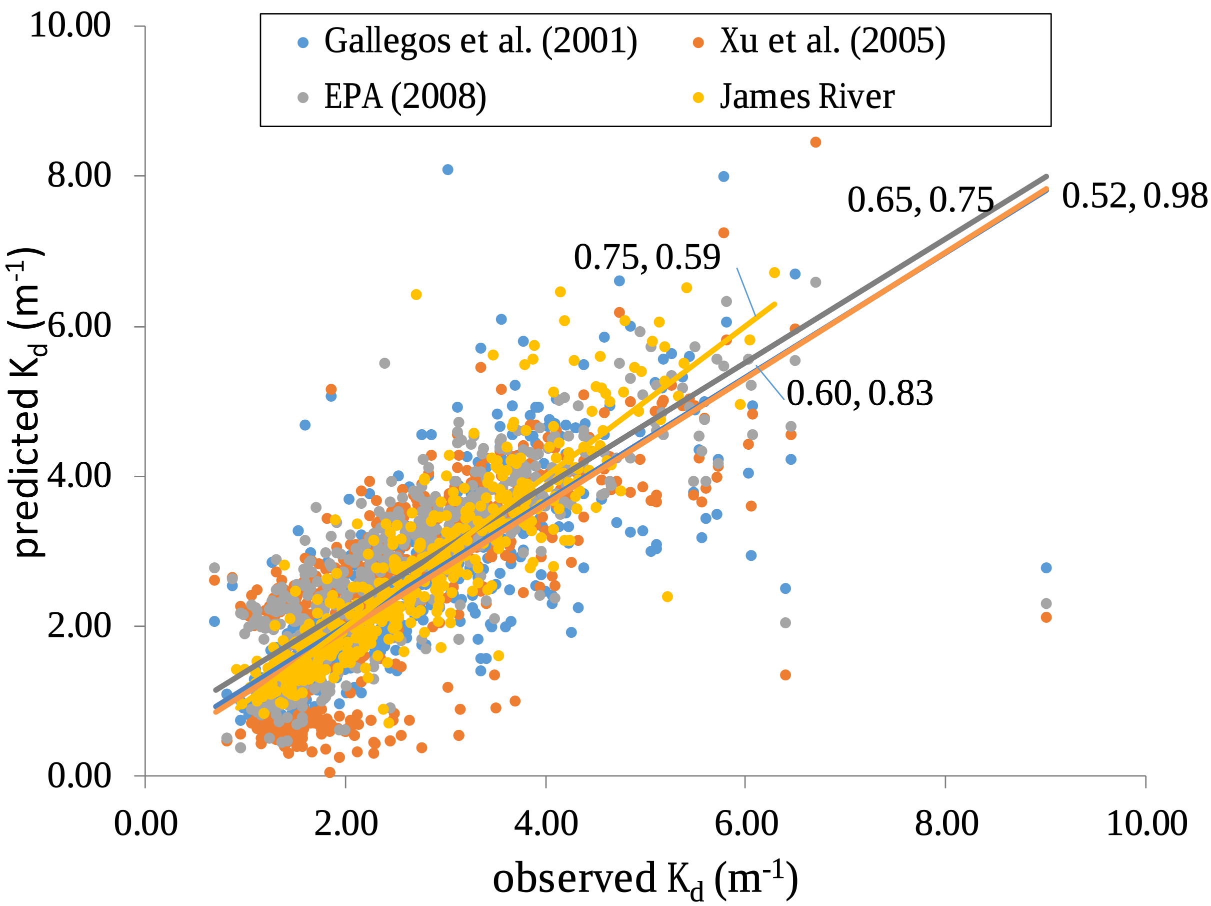


Figure C. Scatterplot of observed K_d (light sensor) versus K_d predicted by published Chesapeake Bay optical models relating chlorophyll-a and TSS or turbidity to K_d. Salinity is a predictor variable in all models except for Gallegos et al. (2001). The R^2 and root mean square error for each linear model is shown. Based on data taken at James River fixed stations during the spring (March-May) and summer (July-September) months, 1993 to 2010.

Appendix D. Chlorophyll-a versus Index of Biotic Integrity Scores

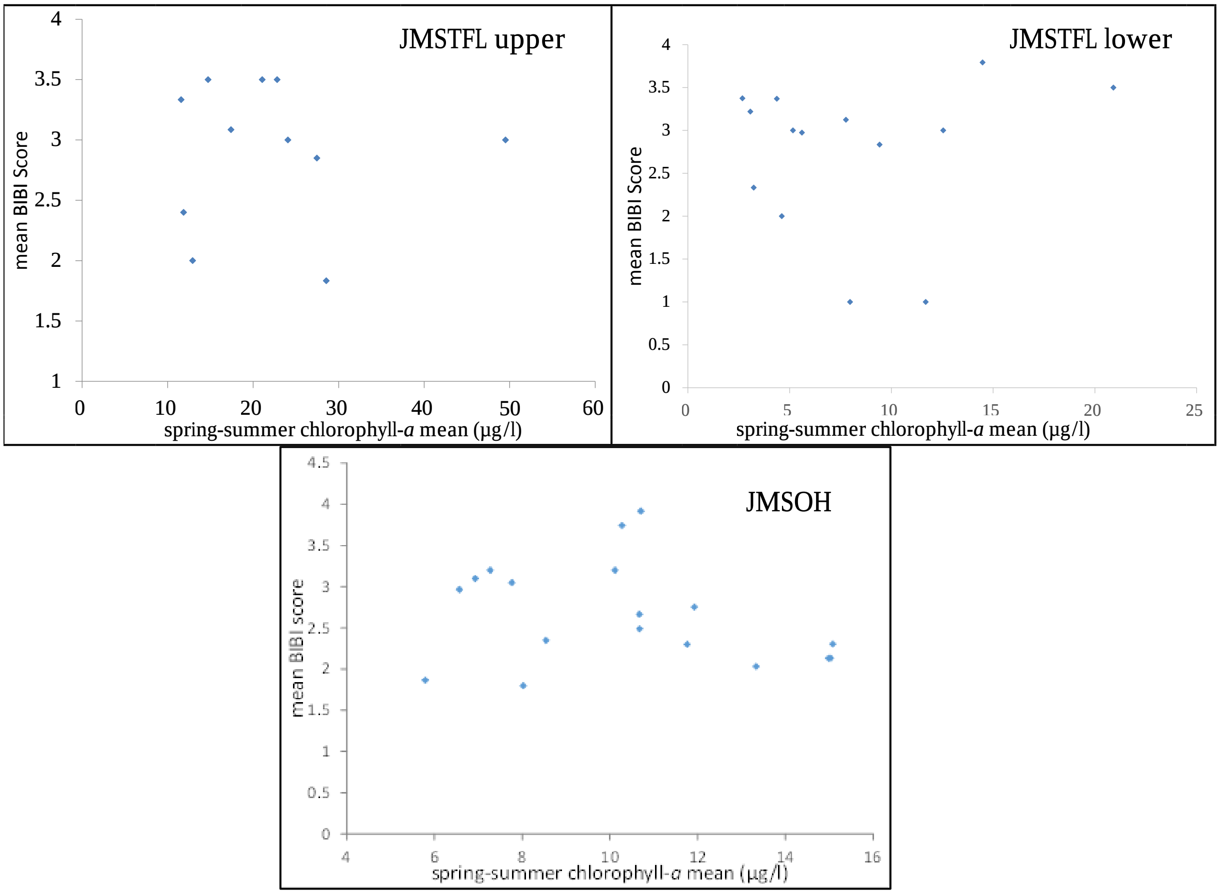


Figure D-1. Scatterplot of spring-summer chlorophyll-a means derived from fixed station datasets and average (summer) BIBI scores from Old Dominion University probabilistic samples, from the years 1996 to 2013. BIBI scores less than 2.67 are associated with degraded benthic communities. No statistically significant correlation was found (Spearman's rank correlation, $p>0.05$).

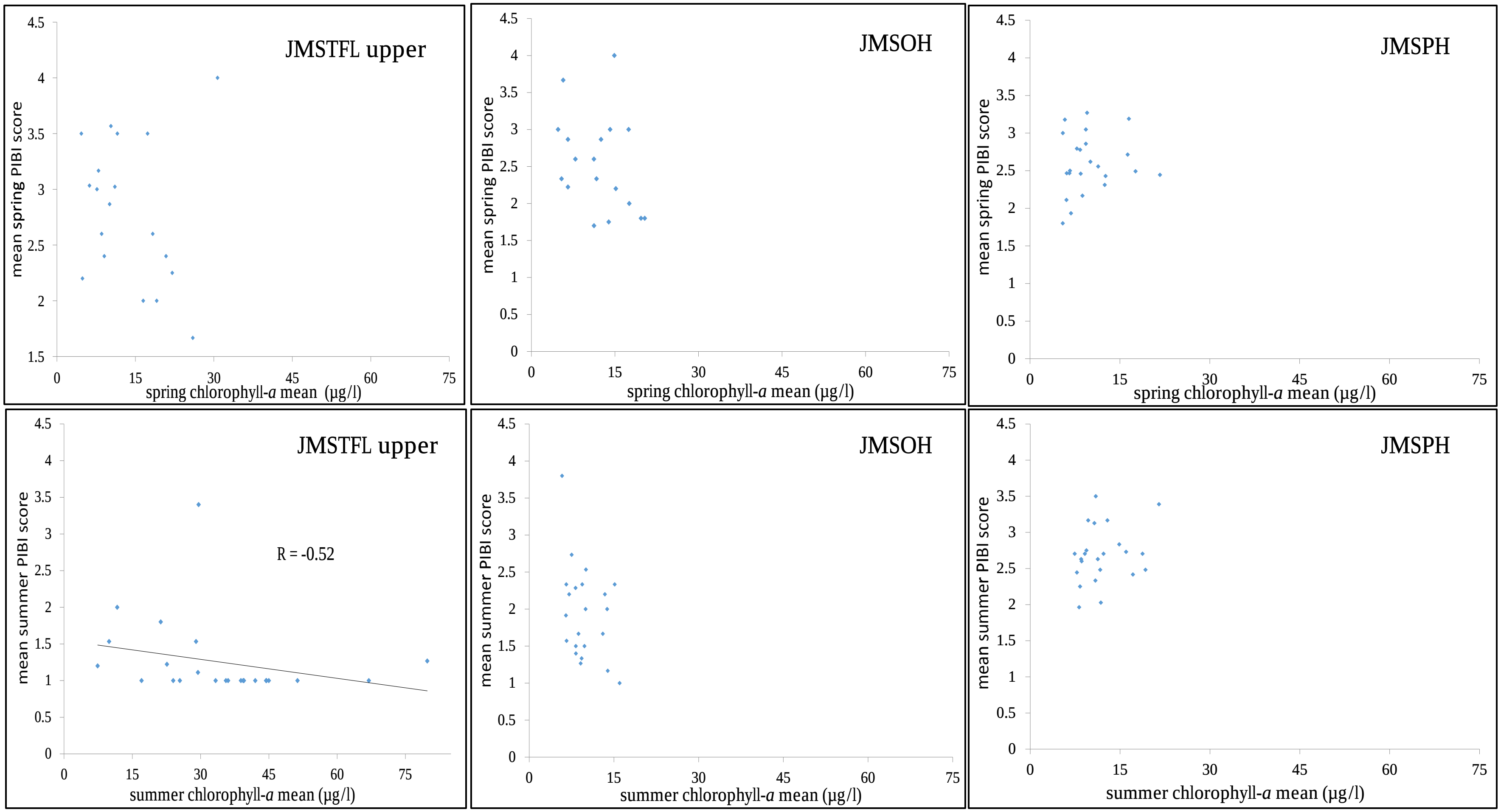


Figure D-2. Scatterplot of spring chlorophyll-a means and average PIBI scores derived from data collected at TF5.5 (left panel), RET5.2 (middle panel) and LE5.5 (right panel) for the spring (top panel) and summer (bottom panel) from 1991 to 2014. PIBI scores below 2.67 are associated with degraded phytoplankton communities. While a statistically significant correlation is detected in the TF5.5 datasets (Spearman's rank correlation, p<0.5), the trend line indicates that phytoplankton communities would still be degraded even when chlorophyll-a is equal to zero.

Appendix E. Chlorophyll-a Trends Across the Chesapeake Bay and James River

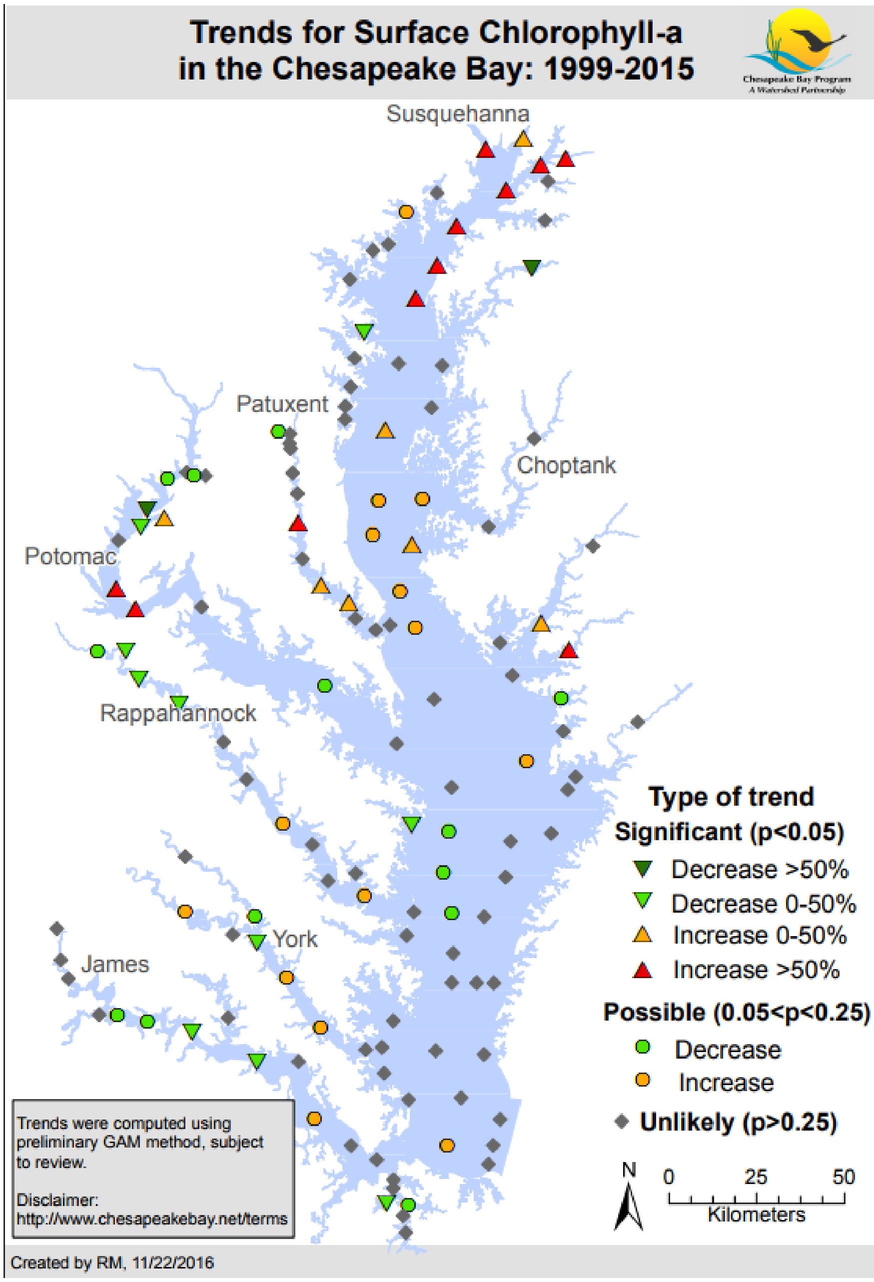


Figure E-1. Map of surface chlorophyll-a trends at long-term fixed stations in the Chesapeake Bay estuary. (Downloaded from the Integrated Trends Analysis Team website on 11/27/2017).

Table E. Trend analysis results for James River chlorophyll-a over the 1985-2017 period using the seasonal Kendal test for monotonic trends. Analysis performed by ODU Chesapeake Bay Program.

Segment	Season	p-value	Sen Slope	% Change in the Baseline	Trend direction
JMSTFU	spring	0.0040	-0.07	-33.23	Improving
JMSTFU	summer	0.3062	-0.04	-26.71	No significant trend
JMSTFL	spring	0.0057	-0.36	-51.94	Improving
JMSTFL	summer	0.7689	-0.10	-11.15	No significant trend
JMSOH	spring	0.4720	-0.04	-18.07	No significant trend
JMSOH	summer	0.3406	-0.04	-17.25	No significant trend
JMSMH	spring	0.6340	0.02	8.88	No significant trend
JMSMH	summer	0.0001	0.11	76.76	Degrading
JMSPH	spring	0.3028	0.04	14.17	No significant trend
JMSPH	summer	0.0000	0.18	147.40	Degrading

Appendix F. Seasonal Mean Chlorophyll-a Concentrations Estimated from Historical Datasets

Table F. Comparison of the recommended chlorophyll-a criteria (µg/L) and estimations of chlorophyll-a central tendency using datasets spanning different periods. Bolded values are baseline criteria.

Segment	Season	Recommended Criterion	1986-2015	1986-1999	2000-2015
JMSTFU	spring	**8**	11	13	10
	summer	21	28	33	26
JMSTFL	spring	**10**	13	16	12
	summer	24	30	37	27
JMSOH	spring	**13**	14	16	15
	summer	**11**	11	13	10
JMSMH	spring	**7**	10	12	10
	summer	**7**	8	7	10
JMSPH	spring	**8**	12	14	11
	summer	7	10	8	12

Appendix G. James River Chlorophyll-a Seasonal Variability Through Time

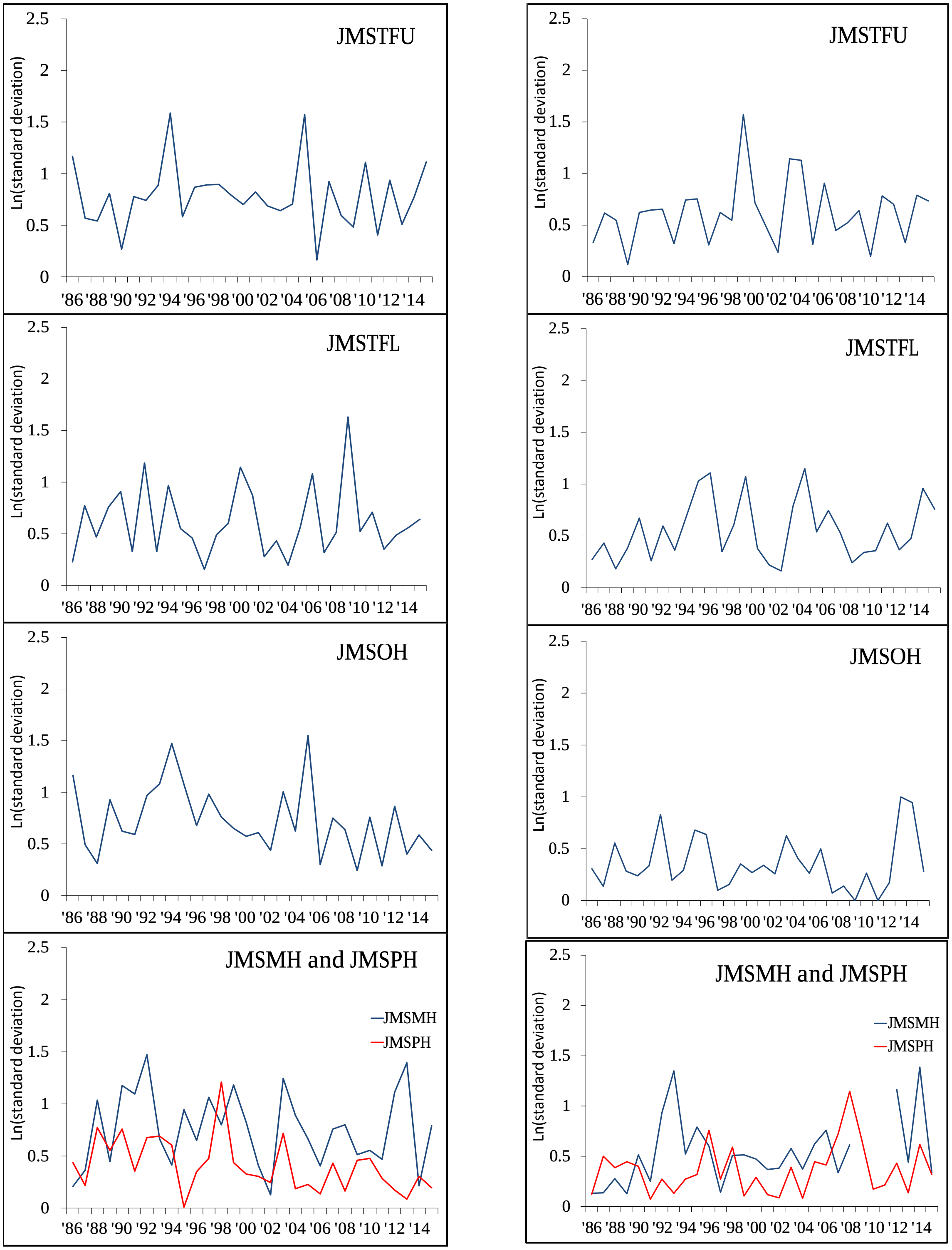


Figure G. Seasonal temporal variation of chlorophyll-a in the tidal James River from 1986 to 2015 derived from fixed station datasets. Spring standard deviations = left panel, summer standard deviations = right panel