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), which was initiated by the Virginia Department of Environmental Quality (VADEQ) in 2011. The work of the JRCS focused primarily on the harmful effects to aquatic life of excessive algae 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 original 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, generating refined datasets which 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 confer optimal protection of the aquatic life designated use with respect to explicit endpoints.

The table below contrasts the original 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 presence of excessive harmful algal-related effects.

Segment-Season	Original	Recommended	Basis for recommended criteria lower than baseline
JMSTFU-spring	10	8	
JMSTFU-summer	15	21	Enhanced protection from harmful algal blooms,elevated pH
JMSTFL-spring	15	10	
JMSTFL-summer	23	23	Enhanced protection from harmful algal blooms,elevated pH
JMSOH-spring	15	12	
JMSOH-summer	22	11	
JMSMH-spring	12	7	
JMSMH-summer	10	7	
JMSPH-spring	12	8	
JMSPH-summer	10	6	Enhanced protection from harmful algal blooms

Introduction

While eutrophication is manifested in the other major regions of the Chesapeake Bay by persistent chronic and acute hypoxia (low dissolved oxygen), this condition is mitigated in the James River estuary by its relatively shallow depth and close proximity to the Atlantic Ocean. Numeric chlorophyll-*a* criteria have been adopted for the James River estuary because they enable the management of watershed nutrient pollutant loads with respect to ecological effects beyond those related to dissolved oxygen (DO). 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 in 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 species 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 warm summer months in the tributaries of the Chesapeake Bay. Toxic HABs typically occur only during the warm weather months as well. Thus, protecting optimal water clarity and pH may be the only concerns in the non-summer months, while the prevention of hypoxia and HABs will be of foremost concern in 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. But depressed DO typically occurs after an algal bloom has crashed, when waters are poorly mixed, so the relationship between chlorophyll-*a* and hypoxia will only be evident by evaluating data that are aggregated over longer periods of time (like a season). 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 only requires optimal water clarity 50% of the time 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. But similar averaging of HAB data would not be appropriate, since lethal HAB occurrences spanning 50% of the season would not be conducive for a healthy aquatic life community. Thus, it is crucial that each algal-related effect be evaluated on the time scale that is appropriate for the impact it elicits in aquatic life.

Lastly, uncertainty vexes all water quality criteria, but especially ones adopted to protect 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, 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— 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[1]) where algal-related impacts have been empirically observed. But developing criteria that protect current conditions requires having a good understanding of what the current condition actually is. Fortunately, an enormous body of monitoring data is available

[1] Pursuant to sections 303 and 101(a) of the Clean Water Act, the federal regulation 40 CFR 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.

for the James River estuary. 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.

Site-specific numeric chlorophyll-*a* criteria were adopted by the Commonwealth of Virginia in 2005 to protect the James River estuary from nutrient-related stressors that negatively affect the "propagation and growth of a balanced, indigenous population of aquatic life" (VSWCB, 2011). The scientific basis for these criteria was questioned once it became apparent that the nutrient cap load set by the Chesapeake Bay Total Maximum Daily Load for criteria attainment (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 basis 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. Much of the research conducted by the SAP was used to inform the recommended modifications to the James River chlorophyll-a criteria (JRCC).

General Methods

Datasets

A variety of information was used to inform the revisions to the JRCC. Data collected using in situ continuous monitors (ConMon[2]) were used to determine chlorophyll-*a* values associated with high pH (>=9.1[3]). More than 20 years' worth of monthly discrete samples collected at the long-term fixed stations supported by the EPA-Chesapeake Bay Program Office (CBPO[4]) (shown in Figure 1) were used to examine relationships between chlorophyll-*a* and low DO, and benthic and phytoplankton community structures. Published equations (Gallegos et al., 2001; Xu et al., 2005; USAEPA, 2008) and historical James River monitoring data were used to elucidate the relationship between chlorophyll-*a* and water clarity in the context of SAV habitat protection. Literature values in addition to laboratory bioassays based on field-collected samples were both used to determine HABs thresholds of concern. Field samples produced the information needed to predict HAB risk from chlorophyll-*a* concentration. Spatially intensive datasets (Dataflow[5]) were used to characterize segment spatial variability, and continuous monitoring data were used to characterize segment temporal variability. Whenever possible, inferences about algal-related effects were based on data collected exclusively in the tidal James River. The methods used for the data collection are described in JRCS-SAP (2016) and the references therein.

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[2] 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.
[3] Per Virginia Water Quality Standards (VSWCB, 2011), the tidal James River cannot exceed a pH of 9.0.
[4] All data collected at fixed stations supported by the EPA-Chesapeake Bay Program are available for download at www.chesapeakebay.net.
[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. Information about these datasets can be found at www.vecos.org, where they can also be downloaded.

Baseline characterizations

At a bare minimum, the revised JRCC are designed to protect baseline conditions as characterized by water quality data gathered in the spring (March-May) and summer (July-September) 2005 to 2015. Protection of baseline conditions prevents degradation of upstream and downstream waters and ensures that natural resources are maintained at their current level. For the tidal fresh (JMSTFU and JMSTFL) and oligohaline (JMSOH) segments, discrete samples taken at fixed stations (Figure 1) and monthly Dataflow datasets were used jointly to establish baseline 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[6]. 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 conservative 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. Downward adjustments were made to the baseline values whenever they were determined to confer inadequate protection of algal-related effects.

Analysis of algal effects

The stressor-response concept (see USEPA, 2010b) was used to determine the nature of relationships between chlorophyll-*a* and hypoxia, elevated pH, reduced water clarity, biological integrity, and HABs. 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.

The JRCC are expressed as seasonal means because they are intended to protect aquatic life from the negative effects of eutrophication that tend to occur over the scale of months. Seasonal means (compared to daily or monthly means) are also prudent targets for watershed modeling. However, algal-related effects can occur quite rapidly (within hours or days). For a seasonal mean criterion to be adequately protective with respect to these more short-term effects, some effort must be made to estimate the probability of exceeding a threshold (one linked to harmful effects) given a central tendency and the typical variability of the site. The JRCS-SAP (2016) and Buchanan (2016) present very different solutions to this problem. But exploiting the cumulative distribution function (CDF)[7] is perhaps the most statistically rigorous way to evaluate the risk of experiencing harmful algae-related effects at different seasonal chlorophyll-*a* means. In statistics, a CDF is typically used to predict the probability of observing a value equal to or less than a specific target, given a specific mean and standard deviation. For instance, one would expect to sample a value less than or equal to 9

[6] Due to the high frequency of Dataflow monitoring in the lower James, Dataflow datasets were used to estimate temporal variability as well as spatial variability. For the tidal fresh and oligohaline segments, daily-aggregated ConMon datasets were used to characterize seasonal temporal variability.
[7] The CDF can be explored using Microsoft Excel's "NORMDIST" function.

approximately 42% of the time when the mean of the population[8] is equal to 10 and the standard deviation is equal to 5. For the purposes of re-deriving the JRCC, the probability of meeting or *exceeding* a specific target was calculated by subtracting the CDF from 1. There is a 58% probability of meeting or exceeding a value of 9 given a mean of 10 and a standard deviation of 5. Not only was the CDF used to evaluate the "riskiness" of different seasonal central tendencies, but it was also used to determine the protectiveness of spatial central tendencies. A spatial central tendency that confers protectiveness for a small, relatively homogeneous waterbody will likely be under-protective for a large, spatially patchy waterbody, even when their temporal dynamics are similar. The spatial and temporal variance structure of each James River segment was characterized using standard deviations derived from interpolated Dataflow chlorophyll-*a*[9] and daily-averaged continuous measurements of chlorophyll-*a*. These standard deviations were used in conjunction with baseline values to construct CDFs. All CDF parameters were log-normalized due to the distributive tendencies of James River chlorophyll-*a* (USEPA, 2010a; VADEQ, 2016).

Risk thresholds

Prediction uncertainty in stressor-response curves, natural variability, and the resiliency of aquatic life to algal-related stressors dictate that chlorophyll-*a* criteria be developed with some degree of "allowable" risk. An overall risk level up to 10% was deemed acceptable for stressors—like HABs and pH—that can cause harmful impacts relatively quickly. This is consistent with the USEPA (2003a) recommendation that waterbodies be allowed to exceed aquatic life criteria 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 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).

Criteria derivation

James Tidal Upper Tidal Fresh (JMSTFU)

<u>Baseline characterization</u>

According to monthly samples taken at the stations TF5.2, TF5.2A, and TF5.3 (Figure 1), chlorophyll-*a* concentrations in the upper tidal fresh segment are the lowest in the estuary. However, Dataflow datasets collected by the Virginia Institute of Marine Science (VIMS) from 2005 to 2008 reveal that chlorophyll-*a* concentrations in this segment are much greater than those indicated by these fixed stations, which are all located in the upper extent of the segment. Grouping analysis of mapped chlorophyll-*a* reveals the presence of two distinct "zones" which meet at approximately river mile 95 (VADEQ, 2016; see Figure 2). While the upper zone is characterized by spring and summer chlorophyll-*a*

[8] A normally distributed population
[9] Dataflow observations were spatially aggregated using the Chesapeake Bay Interpolator grid system in the manner described in VADEQ (2016)

concentrations within the reference ranges compiled by Buchanan (2016), the lower zone has chlorophyll-*a* concentrations quite similar to those observed at stations TF5.5 and TF5.5A, where chlorophyll-*a* tends to be the highest in the estuary. It is for this reason that the baseline values for TF5.5 and TF5.5A were used to estimate the baseline of the lower section of JMSTFU in the absence of more localized information. Effects-based adjustments were only made to baseline values for the lower zone, based on the assumption that chlorophyll-*a* in the upper zone of JMSTFU is already optimally protective of aquatic life.

Spring and summer baseline chlorophyll-*a* concentrations for JMSTFU were calculated by determining the spatial central tendency (median) over each monitoring run from 2005 to 2015, averaging these values over each month-year (median), and then averaging these estimates over each season-year (geometric mean). The upper 99% confidence limit of the arithmetic mean of these values was used to represent the baseline chlorophyll-*a* concentration for each zone. This statistic reflects both inter-annual variability and measurement uncertainty. For the years 2005 to 2008, calculations were based on monthly Dataflow cruises. For the remaining years, the upper zone estimates were derived from chlorophyll-*a* samples taken at stations TF5.2, TF5.2A, and TF5.3 and the lower zone estimates were derived from data taken at stations TF5.5 and TF5.5A (with the exception of summer 2011 and 2012, when a station at river mile 85 was sampled on a semi-monthly basis by Virginia Commonwealth University (VCU)). To determine the segment seasonal mean baseline, area-derived weights (see VADEQ, 2016 for their derivation) were applied to the zone baselines according the following equation: (upper zone mean) x 0.41 + (lower zone mean) x 0.59. Table 1 presents the seasonal means used to calculate the baseline and the final estimates are shown below:

Spring

Upper zone = 3 µg/l, Lower zone = 12 µg/l

Segment baseline = 8 µg/l

Summer

Upper zone = 9 µg/l, Lower zone = 31 µg/l

Segment baseline = 22 µg/l

HAB adjustment (summer only)

Ambient, semi-monthly field samples of the toxin associated with the cyanobacteria *Microcystis aeruginosa* (microcystin) and coincident chlorophyll-*a* concentrations were collected by VCU during the summer months 2011-2013 in the lower portion of JMSTFU (at the station JMS85) and the upper portion of JMSTFL at TF5.5, VCU Rice Center (located at river mile 73), and TF5.5A. There was wide variation in the samples, so different linear and non-linear regression models were explored to enable the most robust predictions of microcystin concentration from observed chlorophyll-*a*. 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 highest R^2 and lowest relative root mean square error was deemed the one with the most predictive power. The best model (Figure 3) was produced from the TF5.5A data, and it predicts that harmful levels of microcystin (0.8 µg/l or greater[10]) are associated with chlorophyll-*a* concentrations that are at or above 49 µg/l. Cumulative distribution functions (CDFs) constructed from the upper 95% confidence limit of Dataflow- and ConMon-derived standard deviation means were used to predict the frequency of exceeding this value in space and time at the baseline central tendency of the lower zone. The baseline summer mean for the lower zone (31 µg/l) was deemed insufficiently protective since an elevated risk of HABs is expected to occur approximately 12% of the time at this seasonal central tendency for a typical season (Figure 4). The spatial and temporal CDFs predict that a summer mean of 30 µg/l confers sufficient protection against harmful *Microcystis* blooms using a 10% risk threshold. Below are the HAB-adjusted summer means:

Summer

Upper zone mean = 9 µg/l, Lower zone mean = 30 µg/l

Segment mean = 21 µg/l

pH adjustment (spring and summer)

According to the linear regression model based on continuous monitoring data (Figure 5) collected in the upper zone of JMSTFL, the chlorophyll-*a* concentration linked to high risk of elevated pH (>=9.1) was determined to be 40 µg/l for the spring and 50 µg/l for the summer. Cumulative distribution functions constructed from the upper 95% confidence limit of Dataflow- and ConMon-derived standard deviation means were used to predict the frequency of exceeding these values in space and time at the baseline and HAB-adjusted central tendencies. The spring baseline mean (12 µg/l) and HAB-adjusted summer mean (30 µg/l) for the lower zone was found to be adequately protective of elevated pH because these central tendencies are associated with predicted spatial and temporal exceedence rates less than 10% (Figure 6). Thus, no adjustments were made to enhance protection from elevated pH.

[10] This concentration was chosen by the JRCS-SAP because of its association with significant declines in the grazing rates of the wedge clam *Rangia cuneata* in laboratory experiments (JRCS-SAP, 2016)

Hypoxia adjustment

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, no adjustment was made to enhance protection against hypoxia.

Water clarity adjustment (spring and summer)

JMSTFU has not achieved its submerged aquatic vegetation (SAV) acreage goals since annual fly-over surveys were first conducted in the 1970s (Orth et al., 2015). Poor water clarity is considered the principal cause of SAV acreage goal shortfalls in the Chesapeake Bay. While this condition is driven mostly by excessive suspended sediments (USEPA, 2003b), phytoplankton can also reduce light transmittance and contribute to a degraded habitat for SAV.

A number of published Chesapeake Bay-specific optical models were examined (Figure 7) to elucidate the relationship between James River chlorophyll-*a*, total suspended solids (TSS) or turbidity, and the light attenuation coefficient K_d—a parameter of water clarity. But (not surprisingly) the model that produced the most accurate predictions of K_d was derived solely from James River water quality samples (spring and summer, 1993 to 2010). The following equation[11] was used to test whether the baseline and HAB-adjusted chlorophyll-*a* means confer adequate protection of optimal water clarity:

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

Because SAV only need optimal water clarity 50% of the time over the growing season (defined here as March 1st through September 30th), this model was used to predict average K_d over the growing season given a growing season chlorophyll-*a* equal to the geometric mean of the baseline and HAB-adjusted values and an average turbidity that is predicted solely from phytoplankton-related particulate matter, using Equation IV-II in Batiuk et al.(2000) and TF5.2/TF5.2A/TF5.3 (upper zone) and TF5.5/TF5.5A (lower zone)-specific regression models relating TSS and turbidity.

Growing season K_d for upper zone = 0.295344 + 0.014785*[5 µg/l] - 0.00229*[0 ppt] + 0.326669*[1 NTU]^0.6667= **0.70 m^{-1}**

Growing season K_d for lower zone = 0.295344 + 0.014785*[19 µg/l] - 0.00229*[0 ppt] + 0.326669*[6 NTU]^0.6667= **1.65 m^{-1}**

where the chlorophyll-*a* values represent the geometric mean of the spring and summer means (i.e., 3 and 9 µg/l for the upper zone, 12 and 30 µg/l for the lower zone).

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

The calculated K_d's are sufficient for optimal SAV growth at application depths[12] 0.5 m and 1.0 m in both zones. The 1.5-m and 2.0-m application depths are protected in the upper zone, but not in the lower zone. But according to the James River model (using the assumptions generated by the other equations), growing season mean chlorophyll-*a* could be equal to zero and the water clarity would still be too poor to support SAV at application depths greater than or equal 1.5 m. This is likely because light scattering in the lower zone is caused by both TSS[13] and colored dissolved organic matter. Since most of the available SAV habitat in JMSTFU is protected at baseline/HAB-adjusted chlorophyll-*a* concentrations and historical SAV beds in this segment appear to have been confined to habitats within the 1-m depth contour (Moore et al., 1999), no adjustments were made to enhance water clarity.

Biological integrity adjustment (spring and summer)

The 2012 and 2014 Benthic Index of Biotic Integrity (BIBI, see Llanso and Dauer, 2002) assessments performed by the CBPO (VADEQ, 2012 and 2016a) found degraded benthic communities in much of the tidal fresh habitat. Probabilistic samples taken in the lower zone of JMSTFU were used in both of these assessments. Stressor analysis has not been recently performed to determine whether excessive algal biomass is a probable stressor of tidal fresh benthic communities, but the last analysis performed could not discern a specific stressor (VADEQ, 2012)[14]. There is no statistical or visual relationship evident between summer average BIBI scores from probabilistic samples and spring-summer chlorophyll-a concentrations[15] at TF5.5 and TF5.5A (Figure 8). For this reason, no adjustment was made for enhanced protection of benthic communities.

While phytoplankton communities appear to be non-degraded in the upper zone of JMSTFU (Egerton and Lane, 2015), Phytoplankton Index of Biological Integrity (PIBI) scores calculated from phytoplankton samples taken at TF5.5 over the past 30 years indicate a degraded phytoplankton community at this site (Buchanan, 2016). Since TF5.5 is representative of conditions in the lower zone of JMSTFU, it is likely that this habitat is also characterized by a degraded phytoplankton community. While nutrients play a role in phytoplankton community structure, water clarity is the most important driver of phytoplankton biological integrity (Buchanan, 2016). This may explain why no statistical or visual relationship is evident between seasonal chlorophyll-*a* means and PIBI scores (Figure 9). Thus, no adjustments were made for enhanced protection of phytoplankton communities.

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[12] The following are the maximum K_d that support the 13% light-through-water requirement for tidal fresh and oligohaline SAV habitats (application depth in parentheses): 4.08 m^{-1} (0.5 m), 2.04 m^{-1} (1 m), 1.36 m^{-1} (1.5 m), and 1.02 m^{-1} (2 m).

[13] The TSS vs. turbidity linear model based on TF5.5 and TF5.5A data had a y-intercept of 4.4 NTU.

[14] The BIBI stressor analysis uses water quality and sediment chemistry data to predict probable causes of benthic impairment in a segment. In the absence of very low DO and sediment contamination, the impairment is classified as having an "unknown cause".

[15] Because BIBI scores reflect the ecological "health" of organisms that have lifespans as long or longer than a season, chlorophyll concentrations were averaged across spring and summer months to maximize the likelihood of detecting associations.

Recommended Criteria for JMSTFU

The following are the recommended JMSTFU chlorophyll-*a* criteria, which when applied in a manner consistent with their derivation should provide adequate protection of the aquatic life designated use:

Spring = 8 µg/l, Summer = 21 µg/l

James River Lower Tidal Fresh (JMSTFL)

Baseline characterization

According to observations taken at the TF5.5 and TF5.5A since 1985, chlorophyll-*a* concentrations in the lower tidal fresh segment are the highest in the estuary. However, spatially intensive (Dataflow) datasets from 2005 to 2008 indicate that chlorophyll-*a* concentrations are not uniform across the segment. Grouping analysis of mapped chlorophyll-*a* reveals two distinct "zones" which meet at approximately river mile 67 (VADEQ, 2016; see Figure 10). The upper zone, represented by stations TF5.5 and TF5.5A, has chlorophyll-*a* concentrations that are considerably higher than what is observed in the lower zone, which is represented by station TF5.6. Baseline chlorophyll-*a* values were determined for these two zones separately. Baseline values for both seasons and zones were evaluated in terms of aquatic life protectiveness and adjusted to the degree deemed appropriate.

Spring and summer baseline chlorophyll-*a* concentrations for JMSTFL were calculated by determining the spatial central tendency (median) over each monitoring run from 2005 to 2015, averaging these values over each month-year (median), and then averaging these estimates over each season-year (geometric mean). The upper 99% confidence limit of the arithmetic mean of these values was used to represent the baseline chlorophyll-*a* for each zone. This statistic was chosen to account for inter-annual variability and measurement uncertainty. For the years 2005 to 2008, estimates were based on monthly Dataflow cruises. For the remaining years, the upper zone estimates were derived from data taken at stations TF5.5 and TF5.5A and the lower zone estimates are derived from data taken at station TF5.6. To determine the segment-wide baseline for each season, area-derived weights (see VADEQ, 2016 for their derivation) were applied to the zone baseline means and the resulting values were summed, as expressed by the following equation: (upper zone mean) x 0.49 + (lower zone mean) x 0.51. Table 2 presents the seasonal means used to calculate the baseline and the final estimates are shown below:

Spring

Upper zone = 12 µg/l, Lower zone = 7 µg/l

Segment baseline = 10 µg/l

Summer

Upper zone = 38 µg/l, Lower zone = 17 µg/l

Segment baseline = 27 µg/l

HAB adjustment (summer only)

Ambient, semi-monthly field samples of the toxin associated with the cyanobacteria *Microcystis aeruginosa* (microcystin) and coincident chlorophyll-*a* concentrations were collected by VCU during the summer months 2011-2013 in the lower portion of JMSTFU (at the station JMS85) and the upper portion of JMSTFL at TF5.5, VCU Rice Center (located at river mile 73), and TF5.5A. There was wide variation in the samples, so different linear and non-linear regression models were explored to enable the most robust predictions of microcystin concentration from observed chlorophyll-*a*. 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 highest R^2 and lowest relative root mean square error was deemed the one with the most predictive power. The best model (Figure 3) was produced from the TF5.5A data, and it predicts that harmful levels of microcystin (0.8 µg/l or greater) are associated with chlorophyll-*a* concentrations that are at or above 49 µg/l. Cumulative distribution functions (CDFs) constructed from the upper 95% confidence limit of Dataflow- and ConMon-derived standard deviation means were used to predict the frequency of exceeding this value in space and time at the baseline central tendency of the lower zone. The baseline summer mean for the upper zone (38 µg/l) was deemed insufficiently protective since an elevated risk of HABs is expected to occur approximately 26% of the time at this seasonal central tendency for a typical season, and 15% of the habitat will be at high risk of HABs at this spatial central tendency (Figure 11). The spatial and temporal CDFs predict that a summer mean of 30 µg/l confers sufficient protection against harmful *Microcystis* blooms using a 10% risk threshold. Thus, an adjustment was made to enhance protection.

Microcystin and chlorophyll-*a* samples were also taken in the lower zone of JMSTFL at station TF5.6. The model created from these data predicts harmful microcystin levels at a chlorophyll-*a* concentration greater than or equal to 32 µg/l (Figure 12). The spatial and temporal CDFs constructed from Dataflow and ConMon-derived standard deviations predict that the summer baseline concentration for the lower zone (17 µg/l) provides sufficient protection against harmful *Microcystis* blooms using a 10% risk threshold (Figure 13). Thus, no adjustments were made to this value to enhance protection.

The following are the HAB-adjusted chlorophyll-*a* means:

Summer

Upper zone mean = 30 µg/l, Lower zone mean = 17 µg/l

Segment mean = 23 µg/l

pH adjustment (spring and summer)

According to the linear regression model based on continuous monitoring data collected in the upper zone of JMSTFL (Figure 5), the chlorophyll-*a* concentration linked to high risk of elevated pH (>=9.1) was determined to be 40 µg/l for the spring and 50 µg/l for the summer. Cumulative distribution functions constructed from the upper 95% confidence limit of Dataflow- and ConMon-derived standard deviation means were used to predict the frequency of exceeding these values in space and time at the baseline and HAB-adjusted seasonal means. The spring baseline mean and HAB-adjusted summer mean for the upper zone was found to be adequately protective of elevated pH because these central tendencies are associated with predicted spatial and temporal exceedence rates less than or equal to 10% (Figure 14). Thus, no adjustments were made to enhance protection from elevated pH.

ConMon 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, no adjustments were made to the spring or summer baseline values for the lower zone with respect to elevated pH.

Hypoxia adjustment

Sustained chronic summer hypoxia in JMSTFL (VADEQ, 2006, 2008, 2010, 2012, and 2016a) has been reported 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 (5.5 mg/l). Bacterial decomposition of algal biomass is a frequent cause of hypoxia in eutrophic waterbodies. However, no relationship is discernible between summer DO percent saturation and spring-summer chlorophyll-*a* means[16] at TF5.6, where almost all of the DO violations have been observed in JMSTFL (Figure 15). For this reason, no adjustment was made to enhance protection against hypoxia.

Water clarity adjustment (spring and summer)

JMSTFL has not achieved its submerged aquatic vegetation (SAV) acreage goals since annual fly-over surveys were first conducted in the 1970s (Orth et al., 2015). Poor water clarity is considered the principal cause of SAV acreage goal shortfalls in the Chesapeake Bay. While this condition is driven

[16] DO concentrations were converted to DO percent saturation, since the latter is not confounded by the effect temperature has on oxygen solubility. Previous estuarine studies have shown that negative correlations between summer DO and chlorophyll-*a* are more likely to be evident when the latter is integrated over multiple seasons rather than just one (Harding et al., 2014; Sutula et al., in review.)

mostly by excessive suspended sediments (USEPA, 2003b), phytoplankton can also reduce light transmittance and contribute to a degraded habitat for SAV.

The James River optical model (Equation 1) was used to test whether the baseline and HAB-adjusted chlorophyll-a means confer adequate protection of optimal water clarity:

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

Because SAV only need optimal water clarity 50% of the time over the growing season (spring and summer months combined), this model was used to predict average K_d over the growing season given a growing season chlorophyll-*a* equal to the geometric mean of the baseline and HAB-adjusted values and an average turbidity that is predicted solely from phytoplankton-related particulate matter, using Equation IV-II in Batiuk et al.(2000) and TF5.5/TF5.5A (upper zone) and TF5.6 (lower zone)-specific regression models relating TSS and turbidity.

Growing season K_d for upper zone = 0.295344 + 0.014785*[19 µg/l] - 0.00229*[0 ppt] + 0.326669*[6 NTU]^0.6667= **1.65 m^{-1}**

Growing season K_d for lower zone = 0.295344 + 0.014785*[11 µg/l - 0.00229*[0 ppt] + 0.326669*[2 NTU]^0.6667= **0.98 m^{-1}**

where the chlorophyll-*a* values represent the geometric mean of the spring and summer means (i.e., 12 and 30 µg/l for the upper zone, 7 and 17 µg/l for the lower zone).

The calculated K_d's are sufficient for optimal SAV growth at application depths[17] 0.5 m and 1.0 m in both zones. The 1.5-m and 2.0-m application depths are protected in the lower zone, but not in the upper zone. But according to the James River model (using the assumptions generated by the other equations), growing season mean chlorophyll-*a* could be equal to zero and the water clarity would still be too poor to support SAV at application depths greater than 1.5 m. This is likely because light scattering in the upper zone is caused by both TSS and colored dissolved organic matter. Since most (~94%) of the total SAV habitat area[18] in JMSTFL is protected at baseline/HAB-adjusted chlorophyll-*a* concentrations and historical SAV growth in this segment appears to have been confined to habitats within the 1-m depth contour (Moore et al., 1999), no adjustments were made to enhance water clarity.

<u>Biological integrity adjustment (spring and summer)</u>

The 2012 and 2014 BIBI assessments performed by the CBPO (VADEQ, 2012 and 2016a) found degraded benthic macrofauna communities in much of the tidal fresh habitat. The majority of the probabilistic samples used in these assessments were taken in JMSTFL. Stressor analysis has not been recently performed to determine whether excessive algal biomass is a probable stressor on the tidal fresh benthic communities, but the last analysis performed could not discern a specific stressor (VADEQ, 2012). There is no statistical or visual relationship evident between average BIBI scores from

[17] The following are the maximum K_d that support the 13% light-through-water requirement for tidal fresh and oligohaline SAV habitats (application depth in parentheses): 4.08 m^{-1} (0.5 m), 2.04 m^{-1} (1 m), 1.36 m^{-1} (1.5 m), and 1.02 m^{-1} (2 m).

[18] This estimate is based on digitized NOAA bathmetry (NOAA, 1998)

probabilistic samples and spring-summer chlorophyll-*a* concentrations at TF5.5 and TF5.5A (Figure 8) or TF5.6 (Figure 16). For this reason, no adjustment was made for enhanced protection of benthic communities.

PIBI scores calculated from phytoplankton samples taken at TF5.5 over the past 30 years indicate that the phytoplankton community in the tidal fresh James is degraded (Buchanan, 2016). While nutrients play a role in phytoplankton community structure, water clarity is implicated as the most important driver (Buchanan, 2016). This may explain why no statistical or visual relationship is evident between seasonal chlorophyll-*a* means and PIBI scores (Figure 9). Thus, no adjustments were made for enhanced protection of phytoplankton communities.

<u>Recommended Criteria for JMSTFL</u>

The following are the recommended JMSTFL chlorophyll-*a* criteria, which when applied in a manner consistent with their derivation should provide adequate protection of the aquatic life designated use:

Spring = 10 µg/l, Summer = 23 µg/l

James River Oligohaline (JMSOH)

<u>Baseline characterization</u>

Spring and summer baseline chlorophyll-a concentrations for JMSOH were calculated by determining the spatial central tendency (median) over each monitoring run from 2005 to 2015, averaging these values over each month-year (median), and then averaging these estimates over each season-year (geometric mean). The upper 99% confidence limit of the arithmetic mean of these values was used to represent the baseline chlorophyll-*a.* This statistic was chosen to account for inter-annual variability and measurement uncertainty. For years 2005-2008 and 2012-2013, calculations were based on monthly Dataflow cruises. For the other years, the calculations were based on data collected at stations RET5.2 and LE5.1. Table 3 presents the seasonal means used to calculate the baseline and the final estimates are shown below:

Spring baseline = 12 µg/l, Summer baseline = 11 µg/l

<u>HAB adjustment (summer only)</u>

There are very few incidents of harmful algae blooms (HABs) in the monitoring record for JMSOH. For this reason, no adjustments were made for enhanced protection against HABs.

pH adjustment (spring and summer)

According to the linear regression model based on continuous monitoring data collected in JMSOH (Figure 17), the chlorophyll-*a* concentration linked to high risk of elevated pH (>=9.1) was determined to be 40 µg/l for the spring and 38 µg/l for the summer[19]. Cumulative distribution functions constructed from the upper 95% confidence limit of Dataflow- and ConMon-derived standard deviation means were used to predict the rate of exceedence of this value in space and time. The baseline values are associated with very small exceedence rates (Figure 18) and thus no adjustments were made for enhanced protection against elevated pH.

Hypoxia adjustment (summer only)

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). Bacterial decomposition of algal biomass is a frequent cause of hypoxia in eutrophic waterbodies. However, no relationship is discernible between summer DO percent saturation and spring-summer chlorophyll-a means at RET5.2 and LE5.1 (Figure 19). For this reason, no adjustment was made to enhance protection against hypoxia.

Water clarity adjustment (spring and summer)

Since 2008, JMSOH has maintained a coverage of submerged aquatic vegetation (SAV) that is equal or greater than the acreage goal set for this segment (Orth et al., 2015). This strongly suggests that the baseline chlorophyll-*a* values are adequately protective of water clarity suitable for SAV growth. Moreover, according to the James River optical model (Figure 7, Equation 1), the growing season mean chlorophyll concentration at baseline—12 µg/l—supports optimal water clarity for oligohaline SAV at all application depths[20]. For these reasons, no adjustments were made.

Biological integrity adjustment (spring and summer)

BIBI assessments performed by the CBPO have consistently determined that benthic communities in JMSOH are degraded (VADEQ, 2008, 2010, 2012, 2016a). Probabilistic samples are the basis of this assessment. Stressor analysis has not been recently performed to determine whether excessive algal biomass is a probable stressor on JMSOH benthic communities, but the last analysis performed could not discern a specific stressor (VADEQ, 2012). There is no statistical or visual

[19] One would expect pH to be less sensitive to algal photosynthesis in JMSOH compared to JMSTFL due to the higher salinity in the former, but this was not found. But it should be noted that JMSOH not only has a higher salinity than JMSTFL, but it also has denser SAV beds. The metabolism of SAV will have a similar impact on pH as that of phytoplankton. Thus, SAV make it easier for phytoplankton to drive up pH to harmful levels. But this will only be the case in shallow water habitats—which is where ConMons were deployed.

[20] Assuming a growing season average salinity of 4 ppt (based on historical data at RET5.2 and LE5.1) and phytoplankton-related turbidity equal to 2 NTU (based on Equation IV-II from Batiuk et al.(2000) and a JMSOH-specific regression equation of TSS versus turbidity), the calculated growing season K_d is 0.98 m^{-1} at the JMSOH chlorophyll-*a* baseline. This value is less than the maximum K_d values listed in footnote 17.

relationship evident between summer average BIBI scores from probabilistic samples and spring-summer chlorophyll-*a* concentrations at RET5.2 and LE5.1 (Figure 20). For this reason, no adjustment was made for enhanced protection of benthic communities.

PIBI scores calculated from phytoplankton samples taken at RET5.2 over the past 30 years indicate that the phytoplankton community in the JMSOH is frequently degraded (Buchanan, 2016). While nutrients play a role in phytoplankton community structure, water clarity is implicated as the most important driver of phytoplankton biological integrity (Buchanan, 2016). This may explain why no statistical or visual relationship is evident between seasonal chlorophyll-*a* means and PIBI scores (Figure 21). Thus, no adjustments were made for enhanced protection of phytoplankton communities.

Recommended Criteria for JMSOH

The following are the recommended JMSOH chlorophyll-*a* criteria, which when applied in a manner consistent with their derivation should provide adequate protection of the aquatic life designated use:

Spring = 12 µg/l, Summer = 11 µg/l

James River Mesohaline

Baseline characterization

Spring and summer baseline chlorophyll-*a* concentrations for JMSMH were calculated by determining the spatial central tendency (median) over each Dataflow monitoring run from 2005 to 2015, averaging these values over each month-year (median), and then averaging these monthly estimates over each season-year (geometric mean). The upper 95% confidence limit of the arithmetic mean of these values was used to represent the baseline chlorophyll-*a* concentration. This statistic was chosen to account for inter-annual variability. Table 4 presents the seasonal means used to calculate the baseline. The final estimates are shown below:

Spring = 7 µg/l, Summer = 7 µg/l

HAB adjustment (summer only)

Ambient field samples of *Cochlodinum* and chlorophyll-*a* concentrations were collected and processed by HRSD and Old Dominion University (ODU) at stations LE5.2, LE5.3, LE5.4, and LE5.5W during the summer 2011-2014. There was wide variation in the samples, so different logistic regression models were explored to enable the most robust predictions of harmful cell densities of *Cochlodinium* from observed chlorophyll-*a*. Relationships were modeled from both individual station datasets and different combinations of pooled datasets (e.g., LE5.2 + LE5.3, LE5.3+LE5.4, LE5.4+LE5.5W). The model producing the greatest area under the receiver operating characteristic curve was deemed the one with the highest predictive power. This model (Figure 22) predicts that the summer chlorophyll-*a* concentration linked to a harmful *Cochlodinium* cell concentration (1,000 cells per ml)[21] is 19 µg/l. Cumulative distribution functions constructed from the upper 95% confidence limit of Dataflow-derived spatial and temporal standard deviation means were used to predict the rate of exceedence of this value in space and time at the baseline central tendency of 7 µg/l. This value was determined to provide adequate protection against HABs because no more than 10% of JMSMH is at risk for HABs at a spatial central tendency of 7 µg/l and the entire segment is not at risk for HABs no more than 10% of the time at the summer central tendency of 7 µg/l (Figure 23). For this reason, no adjustments were made to enhance protection from HABs.

pH adjustment (spring and summer)

Elevated pH (>= 9.1) has been observed in JMSMH via continuous monitoring maintained by HRSD, but only at chlorophyll-*a* concentrations greater than 100 µg/l. Since chlorophyll-*a* values this high occur so infrequently in JMSMH in both space and time at the baseline central tendencies, no adjustment was made to enhance protection against elevated pH.

Hypoxia adjustment (summer only)

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). Bacterial decomposition of algal biomass is a frequent cause of hypoxia in eutrophic waterbodies. However, no relationship is discernible between summer DO percent saturation and spring-summer chlorophyll-a means at LE5.2 and LE5.3 (Figure 24). For this reason, no adjustment was made to enhance protection against hypoxia.

Water clarity adjustment (spring and summer)

JMSMH has not achieved its submerged aquatic vegetation (SAV) acreage goals since annual fly-over surveys were first conducted in the 1970s (Orth et al., 2015). Poor water clarity is considered the principal cause of SAV acreage goal shortfalls in the Chesapeake Bay. While this condition is driven mostly by excessive suspended sediments (USEPA, 2003b), phytoplankton can also reduce light transmittance and contribute to a degraded habitat for SAV.

The James River optical model (Equation 1) was used to test whether the baseline means confer adequate protection of optimal water clarity:

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

[21] This value is the median of cell concentrations linked to 20% mortality (relative to controls) on 33 different types of test organisms. Results were extracted from 7 previously published laboratory studies (JRCS-SAP, 2016).

Because SAV only need optimal water clarity 50% of the time over the growing season (spring and summer), this model was used to predict average K_d over the growing season given a growing season chlorophyll-*a* equal to the geometric mean of the baseline and HAB-adjusted values and an average turbidity that is predicted solely from phytoplankton-related particulate matter, using Equation IV-II in Batiuk et al.(2000) and a JMSMH-specific regression model relating TSS and turbidity.

Growing season K_d = 0.295344 + 0.014785*[7 µg/l] - 0.00229*[18 ppt[22]] + 0.326669*[1 NTU]^0.6667 = **0.68 m^{-1}**

where the chlorophyll-*a* value is the geometric mean of the spring (7 µg/l) and summer (7 µg/l) means.

The calculated K_d is sufficiently protective of water clarity at all application depths[23]. Thus, no adjustments were made for enhanced protection of water clarity.

Biological integrity adjustment (spring and summer)

The 2010 BIBI assessment performed by the CBPO found degraded benthic communities in JMSMH (VADEQ, 2010). Probabilistic samples are the basis of this assessment. A preliminary stressor analysis could not determine the most probable stressor based on these samples (VADEQ, 2010). Because the benthic community is typically assessed as non-impaired, no adjustments were made to enhance benthic biological integrity.

Information about the phytoplankton community is lacking in JMSMH because the segment does not have a long-term phytoplankton monitoring station. For this reason, no adjustment was made for enhanced protection of phytoplankton communities.

Recommended Criteria for JMSMH

The following are the recommended JMSMH chlorophyll-*a* criteria, which when applied in a manner consistent with their derivation should provide adequate protection of the aquatic life designated use:

Spring = 7 µg/l, Summer = 7 µg/l

[22] This is the average salinity over a growing season in JMSMSH, based on samples taken at LE5.3 and LE5.4.
[23] The following are the maximum K_d that support the 22% percent-light-through-water requirement for mesohaline and polyhaline SAV habitats (application depths in parentheses): 3.03 m^{-1} (0.5 m), 1.51 m^{-1} (1 m), and 0.76 m^{-1} (2 m).

James River Polyhaline (JMSPH)

Baseline characterization

Spring and summer baseline chlorophyll-*a* concentrations for JMSPH were calculated by determining the spatial central tendency (median) over each Dataflow monitoring run from 2005 to 2015, averaging these values over each month-year (median), and then averaging these monthly estimates over each season-year (geometric mean). The upper 95% confidence limit of the arithmetic mean of these values was used to represent the baseline chlorophyll-a concentration. This statistic was chosen to account for inter-annual variability. Table 5 presents the seasonal means used to calculate the baseline and the final estimates are shown below:

Spring = 8 µg/l, Summer = 8 µg/l

HAB adjustment (summer only)

Ambient field samples of *Cochlodinum* and chlorophyll-*a* concentrations were collected and processed by HRSD and Old Dominion University (ODU) at stations LE5.2, LE5.3, LE5.4, and LE5.5W during the summer months 2011-2014. There was wide variation in the samples, so different logistic regression models were explored to enable the most robust predictions of harmful cell densities of *Cochlodinium* from observed chlorophyll-*a*. Relationships were modeled from both individual station datasets and different combinations of pooled datasets (e.g., LE5.2 + LE5.3, LE5.3+LE5.4, LE5.4+LE5.5W). The model producing the greatest area under the receiver operating characteristic curve was deemed the one with the most predictive power. This model (Figure 22) predicts that the summer chlorophyll-*a* concentration linked to a harmful *Cochlodinium* cell concentration (1,000 cells per ml) is 19 µg/l. Cumulative distribution functions constructed from the upper 95% confidence limit of Dataflow-derived spatial and temporal standard deviation means were used to predict the rate of exceedence of this value in space and time at the summer central tendency of 8 µg/l. This value was determined to provide inadequate protection because JMSPH is at risk of HABs 16% of the time over a typical season at a summer central tendency of 8 µg/l (Figure 25). The spatial and temporal CFDs predict that a summer mean of 6 µg/l confers sufficient protection against harmful *Cochlodinium* blooms at the 10% risk level, so an adjustment was made accordingly to enhance protection against HABs.

Summer = 6 µg/l

pH adjustment (spring and summer)

Elevated pH (>= 9.1) has not been observed in JMSPH via continuous or discrete monitoring. Thus, no adjustment was made to enhance protection against elevated pH.

Water clarity adjustment (spring and summer)

Since 2009, JMSPH has maintained a coverage of submerged aquatic vegetation (SAV) that is equal or greater than the acreage goal set for this segment (Orth et al., 2015). This strongly suggests that the baseline chlorophyll-*a* values are adequately protective of water clarity suitable for SAV growth. Moreover, according to the James River optical model (Equation 1), the growing season average at baseline—8 µg/l—supports optimal water clarity in polyhaline SAV habitats[24]. For these reasons, no adjustments were made.

Biological integrity adjustment (spring and summer)

The benthic macrofauna community in JMSPH has been consistently assessed as non-impaired. Thus, no adjustments were made to enhance benthic biological integrity.

PIBI scores calculated from phytoplankton samples taken at LE5.5W over the past 30 years indicate that the phytoplankton community in the JMSPH is frequently degraded (Buchanan, 2016). While nutrients play a role in phytoplankton community structure, water clarity is implicated as the most important driver of phytoplankton biological integrity (Buchanan, 2016). This may explain why no statistical or visual relationship is evident between seasonal chlorophyll-a means and PIBI scores (Figure 26). Thus, no adjustments were made for enhanced protection of phytoplankton communities.

Recommended Criteria for JMSPH

The following are the recommended JMSPH chlorophyll-*a* criteria, which when applied in a manner consistent with their derivation should provide adequate protection of the aquatic life designated use:

Spring = 8 µg/l, Summer = 6 µg/l

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[24] Assuming a growing season average salinity of 22 ppt (based on historical data at LE5.3 and LE5.4) and phytoplankton-related turbidity equal to 1 NTU (based on Equation IV-II from Batiuk et al.(2000) and a JMSPH-specific regression equation of TSS versus turbidity), the calculated growing season K_d is 0.69 m^{-1} at the spring baseline/summer HAB-adjusted chlorophyll-*a* means for JMSPH. This value is less than the maximum K_d values listed in footnote 23.

Discussion

As shown in Table 6, most of the recommended criteria are lower than the original criteria (for their derivation, see VADEQ, 2005). The difference can be attributed mainly to the more recent, more sophisticated datasets used to characterize current conditions. The original criteria were derived using information generated solely at fixed stations since spatially-intensive datasets were not available at that time. While fixed stations are adequate for tracking long-term trends, they do not always represent their respective segments very well (VADEQ, 2016). In most segments, it appears that the fixed station datasets tend to overestimate chlorophyll-*a* concentrations compared to the Dataflow datasets. But the fixed stations in JMSTFU grossly underestimate the segment baseline, which is why the revised summer criterion is higher than the original criterion for this segment.

In addition, the measures of central tendency used for the original and revised 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 both temporally (USEPA, 2010a) and for most segments, spatially (VADEQ, 2016). Arithmetic means almost always produce higher estimates than geometric means due to their greater sensitivity to outliers, further explaining why almost all the 2005 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 original 2005 criteria were derived using data compiled from all waters of the Chesapeake Bay rather than exclusively from the James River. While this estuary 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 original 2005 criteria were derived for the purposes of “fish food” protection, not protection against HABs that may produce toxins or physicochemical impacts. The more explicit endpoints of the revised criteria require more precision. Lastly, the protectiveness of the original 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 it cannot be established that the recommended criteria are fully protective of dissolved oxygen concentrations given the limitations of the available monitoring data, at least they 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). 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 exceptions are JMSMH and JMSOH (summer), which require criteria that are established on the basis of protection of space before protection of time. Without site-specific Dataflow and ConMon data, this nuance would be left unappreciated.

In conclusion, 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. The results of the study underscore the importance of reviewing numeric chlorophyll-*a* criteria on a routine basis so that policy decisions always track advances in scientific understanding.

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