Establishing Defensible Chlorophyll *a* Criteria for Protection of the Tidal James River

October 26, 2016

Building from the excellent work of the Scientific Advisory Panel (SAP), we propose that there are several determinations this Regulatory Advisory Panel (RAP) needs to decide upon in order to recommend to the Virginia Department of Environmental Quality a set of defensible, protective tidal James River chlorophyll *a* criteria. At the August 10, 2016 RAP meeting, for each of these decisions, we presented various options moving forward, with pros and cons for each and justification for our proposed decision. Within this paper, following up on that presentation and the excellent feedback received from fellow RAP members, we explain and document the approach for deriving chlorophyll *a* criteria which arises from these decisions which we believe are the most scientifically defensible for establishing numeric chlorophyll *a* criteria in the tidal James River.

Respectively submitted,

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Decisions Needed to Establish Scientifically Defensible Chlorophyll *a* Criteria

Reference conditions vs. effects-based approach

Claire Buchanan (ICPRB) provided the SAP with ranges of chlorophyll *a* concentration values derived from historic observations of elevated water quality conditions, or reference conditions. This analysis was based on historical observations (1950s-current) from a variety of Chesapeake Bay tributaries, including but not limited to the tidal James River (Buchanan 2016). This report attempted to provide a range of values which are reflective of pristine water quality conditions, prior to degradation. Reference conditions are commonly used to develop water quality criteria for nutrients.

The main benefit of utilizing reference chlorophyll *a* concentrations is that they represent our best estimate of conditions in the tidal James River prior to degradation and further, achieving these concentrations would be very protective of aquatic life, including negative impairments which have not been documented. The downside to this approach is that our current understanding of reference conditions is largely built upon data from other tidal tributaries to the Chesapeake Bay and, thus, raises questions as to whether these values truly represent reference conditions for the tidal James River. As a result, there are questions about what these reference condition concentrations specifically represent in terms of protection of aquatic life.

In order to establish an effects-based approach, the Scientific Advisory Panel compiled high frequency spatial and temporal data from a 10-year period (2004-2014) in the tidal James River in combination with data sets documenting ecological impairments associated with algal blooms. Direct relationships between chlorophyll *a* concentrations and adverse ecological and water quality impairments were established specific to season-segments which indicated the proportion of time that impairments would be expected to occur in association with various chlorophyll *a* concentrations. This approach was performed using arithmetic seasonal mean values, however, Virginia's current and proposed chlorophyll *a* criteria assessment procedures utilize geometric means which is fully consistent with EPA's published Chesapeake Bay chlorophyll *a* criteria guidance. This issue is discussed further in the next section.

The advantage of effects-based protective ranges of chlorophyll *a* concentrations is that they are based upon season- and segment-specific effects based impacts of algae to aquatic life in the tidal James River using multiple lines of evidence. The disadvantage of using these protective ranges is that they rely upon only those ecological impairments which have been documented in this study, which are unlikely to include all forms of algae-related aquatic life impacts (e.g., such as other species of harmful algae [see recent blooms of *Alexandrium monilatum]*, food web implications, etc.).

While there are some limitations to using an effects based approach, this provides the strongest, quantitative connections between ambient chlorophyll *a* concentrations and recognized, and documented adverse impacts on the James River estuarine ecosystem currently available. As a result, we suggest moving forward with the effects based approach.

Measures of central tendency

The Scientific Advisory Panel has discussed two potential approaches to measuring the central tendency of chlorophyll *a* data. Arithmetic means have been considered because in certain situations, these values illustrate stronger correlation coefficients (R^2) associated with threshold exceedances. Arithmetic means also represent the original basis for the tidal James River chlorophyll *a* criteria published in 2005. The disadvantage of using arithmetic means is that Virginia DEQ's current and proposed criteria assessment methods utilize geometric means, fully consistent with published EPA Chesapeake Bay chlorophyll *a* criteria guidance (EPA 2010) and the peer-reviewed scientific literature (e.g. Harding et al. 2014). This is justified on the basis that because chlorophyll typically exhibits a log-normal

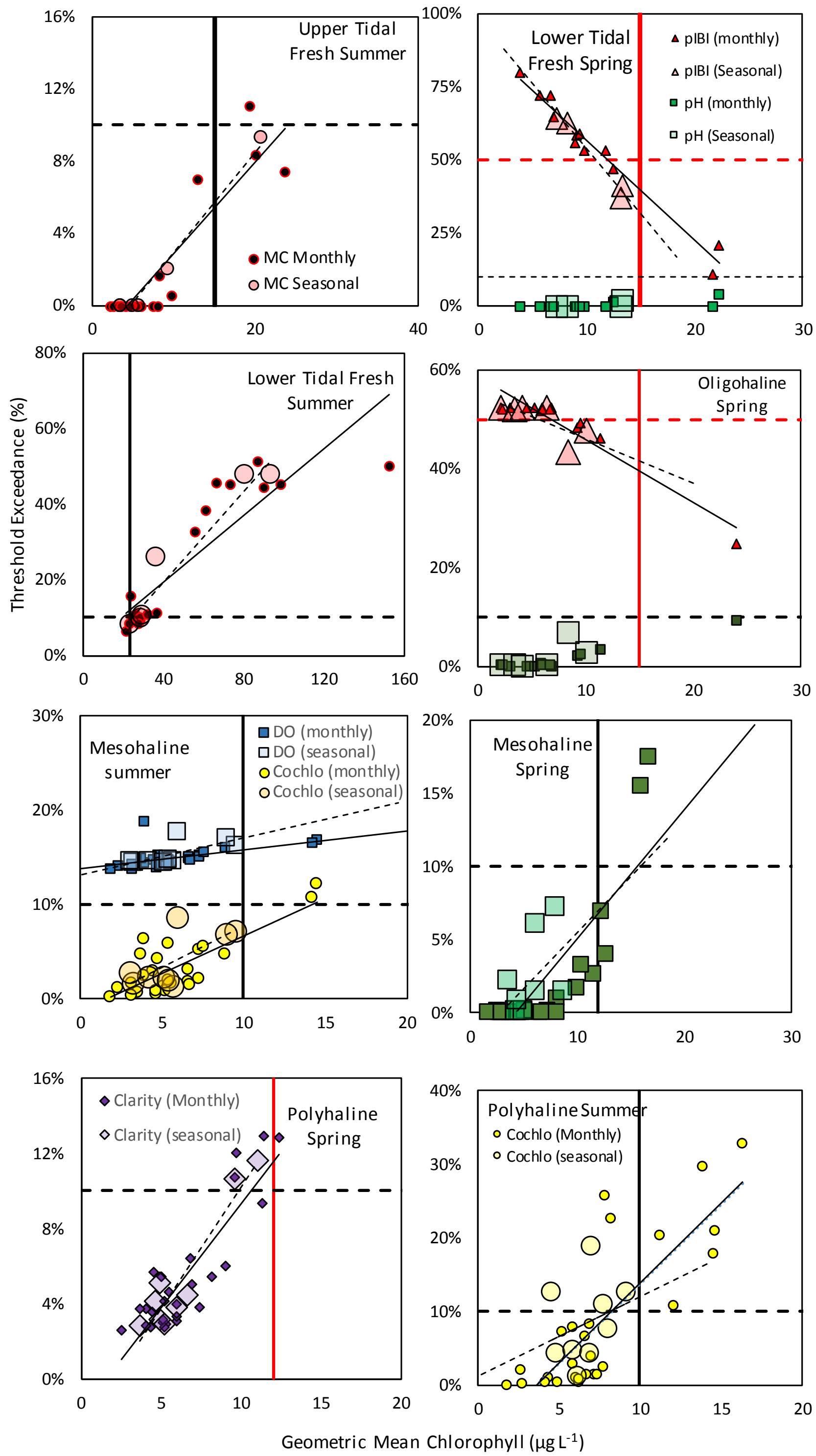

Figure 1. Comparison between seasonal geometric means and monthly geometric means as predictors for threshold exceedances in the tidal James River. Large symbols in all plots indicate seasonal values while small symbols indicate monthly values. Dashed regression lines are for seasonal values while solid regression lines are for monthly values.

distribution, it is more accurately summarized with a geometric mean. As a result, establishing chlorophyll *a* criteria based upon arithmetic relationships which, in turn, would be assessed upon the geometric means would be inconsistent and un-protective.

Arithmetic Means:

$$[\bar{a}_{\text{arithmetic}} = (a_1 + a_2 + a_3) / n_a]$$

Geometric Means:

$$[\bar{a}_{\text{geometric}} = \sqrt[n_a]{(a_1 * a_2 * a_3)}]$$

Alternatively, the use of geometric means is fully consistent with Virginia's existing Chesapeake Bay water quality standards chlorophyll *a* criteria assessment procedures, the Chesapeake Bay Program (CBP) Criteria Assessment Procedures Workgroup's recommended revised chlorophyll *a* criteria assessment procedures, and EPA's published Chesapeake Bay chlorophyll *a* criteria guidance. While there have been challenges showing strong relationships between geometric means and threshold exceedances in the mesohaline and polyhaline James River when using seasonal means; monthly geometric means and threshold exceedances illustrate strong relationships (Figure 1 & 2, see next section for further details). The use of geometric means in the

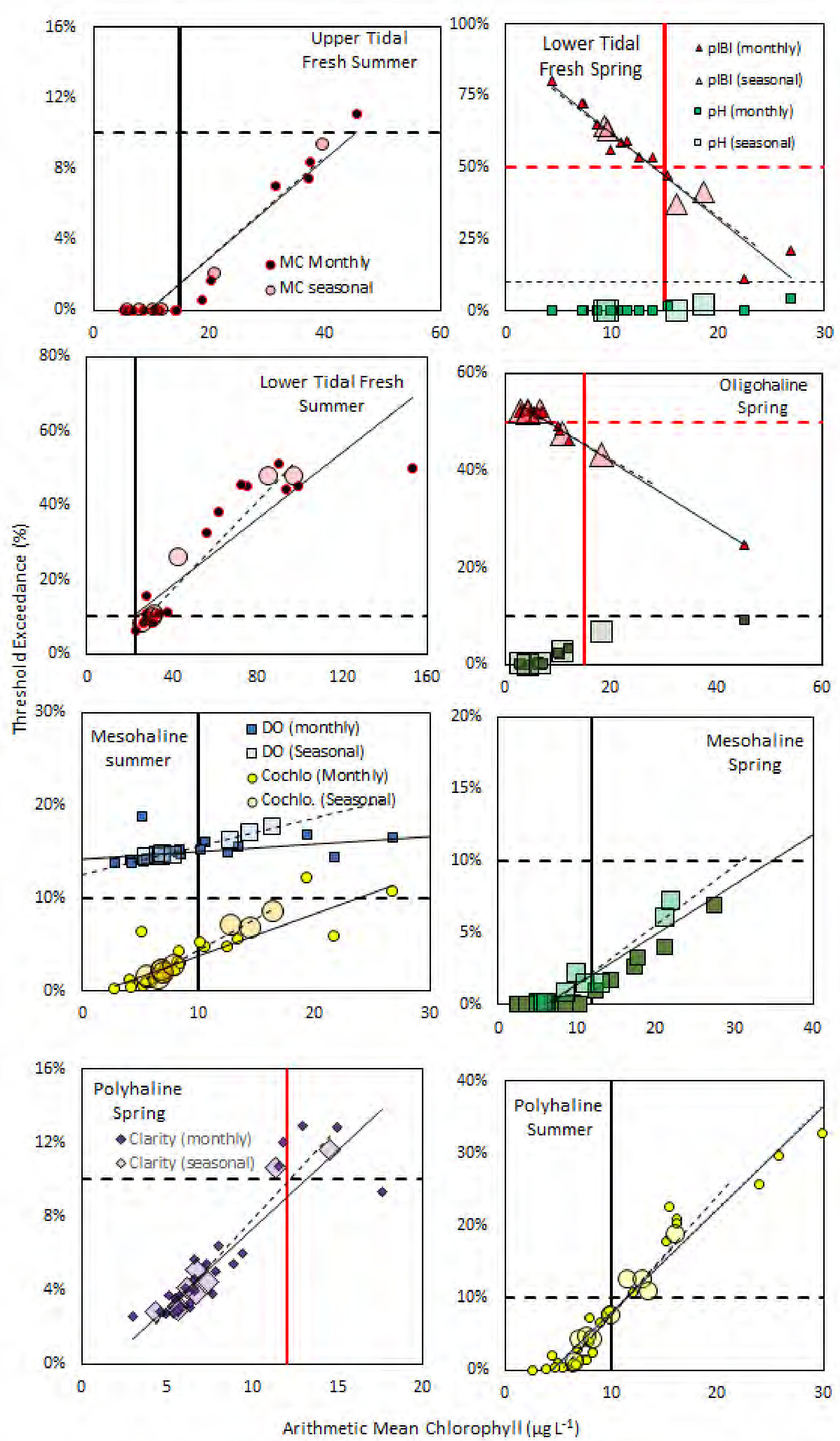

Figure 2. Comparison between seasonal arithmetic means and monthly arithmetic means as predictors for threshold exceedances in the tidal James River. Large symbols in all plots indicate seasonal values while small symbols indicate monthly values. Dashed regression lines are for seasonal values while solid regression lines are for monthly values.

analysis of chlorophyll *a* concentrations have been published in the peer-reviewed scientific literature and have been recommended by EPA in its Chesapeake Bay chlorophyll *a* criteria guidance developed by the CBP Criteria Assessment Procedures Workgroup and approved by the CBP partnership prior to EPA publication in 2010 (U.S. EPA 2010). While these geometric mean relationships are statistically significant, we recognize they are not as strong as arithmetic mean relationships.

Regardless, we recommend the use of geometric means in order to maintain consistency with the peer-reviewed scientific literature, EPA's 2010 Chesapeake Bay chlorophyll *a* criteria guidance, Virginia's existing Chesapeake Bay water quality standards' assessment procedures and CBP Criteria Assessment Procedures Workgroup's recommended revised chlorophyll *a* criteria assessment procedures. While arithmetic relationships with threshold exceedances do improve the strength of these relationships, the statistical significance and strong correlation coefficients associated with monthly geometric means establishes this approach as scientifically defensible (Figures 1 and 2).

Averaging periods for criteria development

As mentioned above, the use of monthly means significantly improves the resolution of the relationships between chlorophyll *a* concentration means and the threshold exceedances. These monthly relationships provide more reliable relationships between geometric means and threshold exceedances most notably in the mesohaline and polyhaline James River segments (Figure 3). Derivation of chlorophyll a criteria using geometric means also ensure consistency between the criteria assessment procedures and criteria derivation. The sample sizes associated with these means are also more similar to actual data availability due to high frequency data collection associated with recent monitoring (see Figure 1). Finally, monthly means are the best averaging period reflecting the actual timeframes at which algal blooms have their adverse effect on the tidal James River ecosystem. Algal blooms last for days to weeks, not entire seasons.

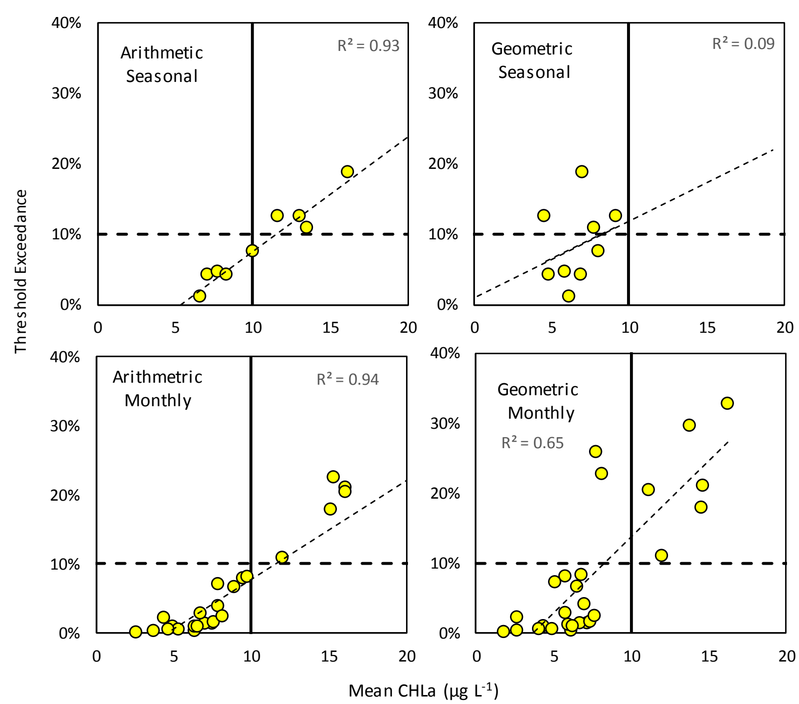

Figure 3. Comparison between seasonal arithmetic means and monthly geometric means as predictors for *Cochlodinium* threshold exceedances (1,000 cells mL^{-1}) in the polyhaline summer.

We recommend utilizing monthly means for purposes of criteria derivation, because this provides for significantly improved resolution of the relationships between chlorophyll *a* geometric means and the threshold exceedances, specifically for the mesohaline and polyhaline James River segments. Alternative approaches do exist which require conversion of derived values from arithmetic to geometric but this would involve incorporating data sets external to the tidal James River which would not be preferred.

Relative importance of the individual lines of evidence

This comprehensive analysis has recognized multiple metrics which degrade aquatic life. These metrics have varying degrees of importance when it comes to protecting aquatic life in the tidal James River. While we acknowledge defining the absolute magnitude of impact to aquatic life for these various metrics is problematic due to variable threshold scales, we suggest there are some factors which can be considered and utilized and that the SAP established a threshold for each metric that is expected to correspond to a category of aquatic life effects. First, in terms of suitability, we suggest it is most important to consider metrics which are not protected against with any other criteria already adopted into Virginia's Chesapeake Bay water quality standards. Specifically, this would include biological resource responses—harmful algal blooms (HABs) and the Chesapeake Bay Program's phytoplankton index of biotic integrity (PIBI). Second, in terms of magnitude of impacts, HABs have been directly associated with mortality in the case of *Cochlodinium (*Mulholland et al. 2009, Reece & Vogelbein 2015) and feeding inhibition and accumulation of carcinogenic toxins in the case of Microcystin (Wood et al. 2014, Bukaveckas et al. 2014) at the level of threshold utilized in this analysis. These impacts represent a greater threat than any other metric documented in this study and thus we consider these issues most threatening to aquatic life. While dissolved oxygen (DO) and pH can also lead to mortality and other impacts, the thresholds for this study utilized a lower bar of impact than HABs. Finally, given that these criteria are intended to establish protective nutrient loading rates it may be important to consider factors which are degraded by other environmental influences (such as sediment). This would lead to a de-emphasis upon water clarity and PIBI.

Based upon this rationale we consider the following to be the strongest ranking process for these metrics:

1. HABs – biological indicator which is otherwise unprotected by other Virginia Chesapeake Bay water quality standards and a direct consequence of excessive nutrient loading
2. pIBI – biological indicator which is otherwise unprotected by other Virginia Chesapeake Bay water quality standards but is degraded by other environmental factors in addition to nutrient loading (e.g., sediment loads)
3. DO – physiochemical factor which is already addressed by other Virginia Chesapeake Bay water quality standards, and driven by algal blooms
4. pH – physiochemical factor which is already addressed by other Virginia Chesapeake Bay water quality standards, and driven by algal blooms but also other environmental factors and pollutants
5. Clarity – physiochemical factor which is already addressed by other Virginia Chesapeake Bay water quality standards, and driven by algal blooms but also

other potential pollutants and at times dominated by other pollutants (e.g., suspended sediments)

Addressing the two segment seasons with no empirical evidence of adverse impairments

In two season-segments, no observations of adverse impairments were observed thus preventing the ability to evaluate a defensible range. That being said, in these two season-segments no observations of non-attainment of the existing James River chlorophyll *a* criteria were observed which likely prevented documentation of harmful effects (Figure 4). Furthermore, impacts associated with algal blooms have been documented in both of these segments in different seasons so there is reasonable evidence to suggest aquatic life impacts could occur in the future. Finally, the original criteria were established using a sound approach that has generally been qualified by this study. As a result, we recommend keeping the existing published chlorophyll *a* criteria for the upper tidal fresh spring segment and oligohaline summer segment.

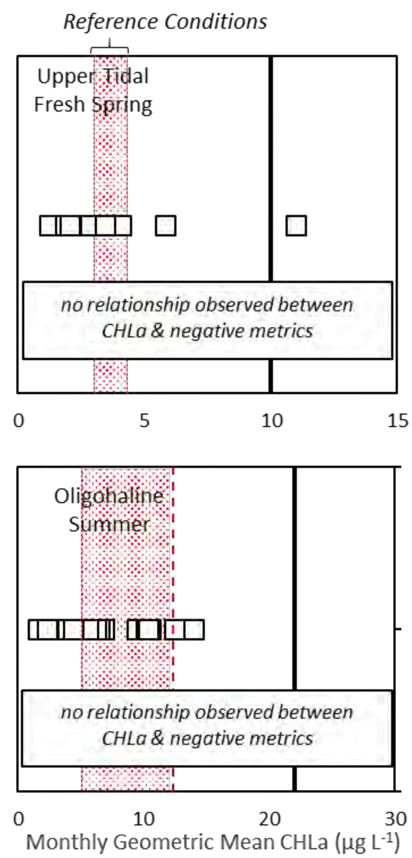

Figure 4. (*right*) Monthly geometric chlorophyll *a* values (white squares) for the upper tidal fresh (spring) and oligohaline (summer) tidal James River over the course of the SAP's data collection period relative to current criteria (black vertical lines). The red hatch marked areas represent proposed reference conditions from Buchanan 2016.

Proposed Approach for Establishing Numeric Chlorophyll *a* Criteria

As a result of the previously outlined rationale, we recommend that utilizing linear models between the fixed threshold exceedance rates and monthly geometric mean chlorophyll *a* concentrations is the most scientifically defensible and objective approach for the development of chlorophyll *a* criteria in the tidal James River. Previously, we referenced defensible ranges included in the SAP report (Bukaveckas et al. 2015, Tango 2015) in addition to this approach, however, the incorporation of these ranges is problematic for several reasons. First, we were unable to replicate the approach documented in the SAP report in order to establish ranges based upon geometric mean values. Second, even with the establishment of such defensible ranges, a specific value needs to be identified for setting a criterion. Finally, we believe the use of linear models to project chlorophyll *a* concentrations provides a clear, objective method for establishing criteria consistently across all tidal James River season-segments. Here we outline the specific details of this criteria derivation approach as well as the results for each season-segment combination.

Table 1. Summary of tidal James River chlorophyll *a* concentration data used in criteria derivation analysis.

Segment	Season	Years of Data availability	seasonal Low ($\mu g\ L^{-1}$)	seasonal High ($\mu g\ L^{-1}$)	seasonal # of years	monthly Low ($\mu g\ L^{-1}$)	monthly High ($\mu g\ L^{-1}$)	monthly # of months	High Resolution data type
Upper Tidal Fresh	Spring	NA							
	Summer	2009-2014	3.5	20.9	6	2.4	23.8	18	Weeky
Lower Tidal Fresh	Spring	2011-204	7.3	13.3	4	3.9	22.3	12	Weekly
	Summer	2009-2014	23.7	93.6	6	21.5	152.3	18	Weekly
Oligohaline	Spring	2005-2007, 20012-2013	2.1	10.1	5	2.1	24	15	Dataflow
	Summer	NA							
Mesohaline	Spring	2005-2013	3.6	8.8	9	1.7	16.6	27	Dataflow
	Summer	2005-2013	3.1	9.5	9	1.9	14.5	27	Dataflow
Polyhaline	Spring	2005-2013	3.6	11.1	9	2.5	12.4	27	Dataflow
	Summer	2005-2013	4.7	9.3	9	1.8	16.3	27	Dataflow

Methods

Establishing threshold exceedances

Monthly estimates of threshold exceedances were determined using all available concurrent observations of segment and season specific metric impairments and chlorophyll a concentration data in addition to all available high frequency chlorophyll data (Table 1). First, the proportion of impairments (observations of metrics greater than SAP established thresholds, see Table 2 in the SAP report) associated with chlorophyll *a* concentration ranges (arrayed in 10 μg^{-1} bins) was established for each metric that exhibited a significant relationship with chlorophyll *a* concentration. This approach is identical to that used in the SAP report. Second, using all available high-resolution chlorophyll *a* concentration data, we calculated the proportion of observed chlorophyll *a* concentration values for each *month* associated with the previously mentioned $10\mu gL^{-1}$ bins across all season segments. Third, the combined probability of threshold exceedance for each *month* was derived by multiplying these probabilities together and

Table 2. (right) An example calculation for July 2005 in the Polyhaline Summer for how each estimate of monthly threshold exceedance was derived.

CHLa ($ug\ L^{-1}$)	Probablity of Cochlo. impairment (based upon all concurrent observations of CHLa & Cochlo. in the season-segment)	Array distribution of Chlorophyll observations (July 2005)	Combined probability (column 2 * column 3)
0-10	0%	8%	0.0%
10-20	11%	78%	8.7%
20-30	60%	12%	7.5%
30-40	100%	2%	1.8%
40-50	50%	0%	0.0%
50-60	67%	0%	0.0%
60-70	100%	0%	0.0%
70-80	92%	0%	0.0%
80-90	92%	0%	0.0%
>90	92%	0%	0.0%
		Total expected threshold exceedance	17.9%
		Monthly geometric mean Chlorophyll ($\mu g\ L^{-1}$)	14.6

summing across bins to determine the expected threshold exceedance for that *month* (Table 2). This approach was identical to that taken by the SAP with the exception that we focused upon geometric monthly means versus arithmetic seasonal means for the reasons documented previously on pages 2-4.

Deriving criteria from threshold exceedances

In order to utilize this analysis to establish recommendations for numeric chlorophyll *a* criteria, we consider linear regressions of monthly geometric mean chlorophyll *a* concentrations and expected threshold exceedances. These models were used to establish criteria on the following terms. First, where multiple metrics were available we focused upon the metric considered most important for chlorophyll *a* criteria derivation (see *Relative importance of the individual lines of evidence* on pages 4-5). For these relationships we determined regression line equations and subsequently evaluated the chlorophyll value at which a 10% threshold exceedance is expected for HABs, pH, and water clarity and at which a 50% threshold exceedance is expected for PIBI. These levels of exceedance were chosen due to their consistency with EPA published Chesapeake Bay water quality criteria guidance (U.S. EPA 2003).

Table 3. Summary of the proposed tidal James River chlorophyll *a* criteria for each segment-segment along with the respective regression coefficients. Values in orange indicate a decrease relative to current criteria whereas values in green indicate an increase relative to current criteria.

Segment	Season	Current Criteria	Change needed?	Proposed Criteria	Metric Basis	Y-Int	Slope	p Value	R^2
Upper Tidal Fresh	Spring	10	No	10	previous criteria	n/a	n/a	n/a	n/a
	Summer	15	Yes	24	HAB (MC)	-0.023	0.005	<0.0001	0.83
Lower Tidal Fresh	Spring	15	Yes	12	pIBI	0.913	-0.034	<0.0001	0.97
	Summer	23	Yes	19	HAB (MC)	0.016	0.004	<0.0001	0.78
Oligohaline	Spring	15	Yes	7	pIBI	0.586	-0.013	<0.0001	0.90
	Summer	22	No	22	previous criteria	n/a	n/a	n/a	n/a
Mesohaline	Spring	12	Yes	16	pH	-0.038	0.009	<0.0001	0.70
	Summer	10	Yes	14	HAB (Cochlo.)	-0.014	0.008	<0.0001	0.64
Polyhaline	Spring	12	Yes	11	Clarity	-0.018	0.011	<0.0001	0.78
	Summer	10	Yes	8	HAB (Cochlo.)	-0.079	0.022	<0.0001	0.65

Results & Conclusions

Relationships between Chlorophyll and Threshold exceedances

Monthly means of monitored chlorophyll *a* concentrations, which expanded the sample sizes by 3 fold, resulted in a greater range of chlorophyll *a* concentration values (Table 1) which, in turn, improved the strength of the season-segment linear regressions (see Figures 1 and 2). Linear models between monthly geometric mean chlorophyll and threshold exceedances were significant ($p < 0.0001$) in all cases with strong R^2 values ranging from 0.64 to 0.97 (Table 3). Non-linear relationships were also evaluated; however, in most cases, these did not provide substantial improvements.

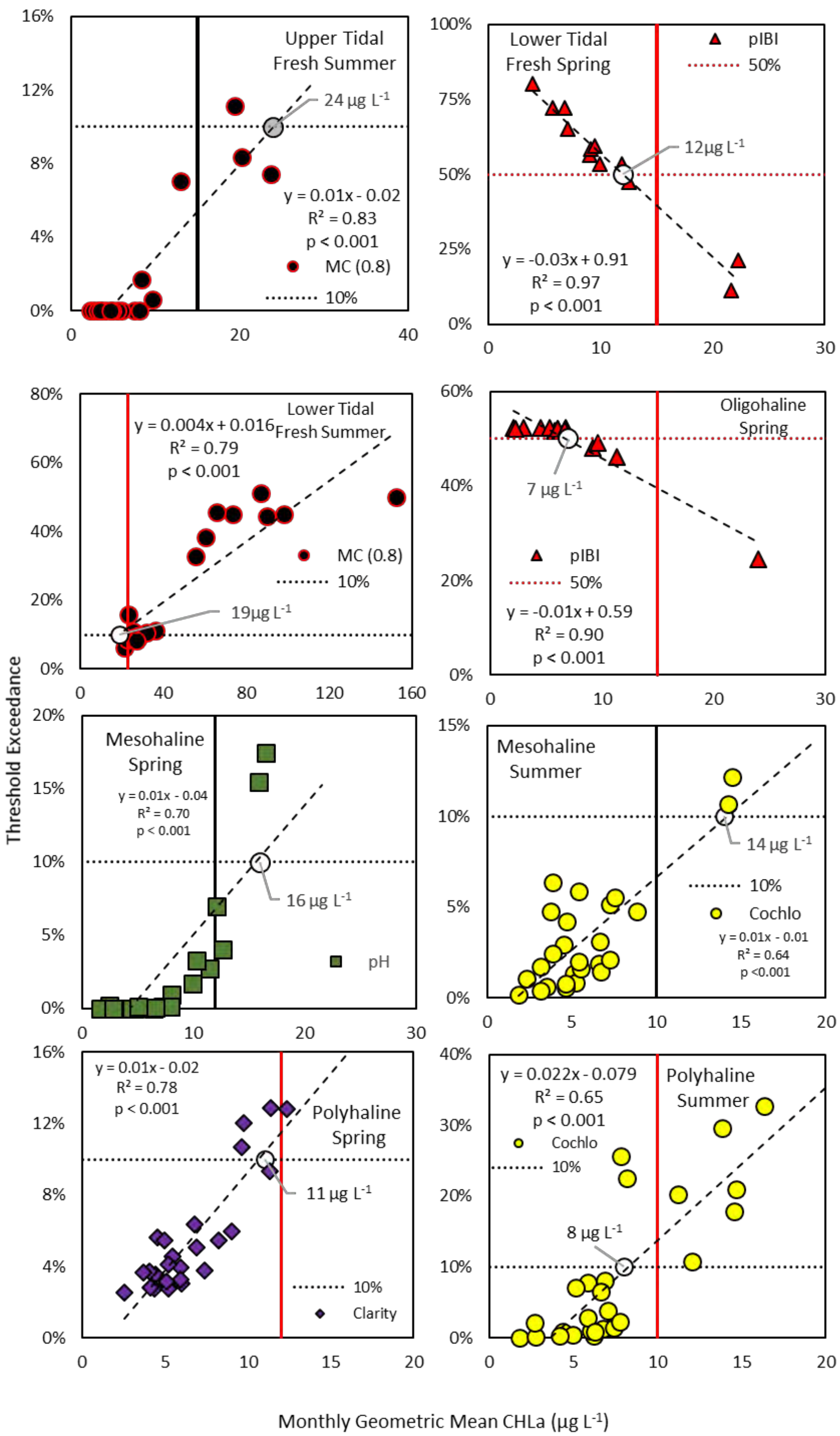

Figure 5. Recommend chlorophyll criteria (white circles) established using linear regressions between monthly geometric chlorophyll *a* values and combined probability threshold exceedances. Vertical lines indicate current criteria (red where a reduction is needed). Dashed horizontal lines indicate 10% (black, HABs, Clarity, pH) and 50% (red; PIBI) standard threshold exceedance rates

Projected chlorophyll *a* concentrations associated with fixed threshold exceedances (10% for HABs, pH and water clarity and 50% for PIBI) resulted in recommendations for chlorophyll *a* criteria that were lower than Virginia's existing chlorophyll *a* criteria in five segment-seasons and higher than Virginia's existing chlorophyll *a* criteria in three segment-seasons (Figure 5). These values differed from current criteria from 1 to 9 µg L-1 with the largest differences occurring in the Upper Tidal Fresh Summer and the Oligohaline Spring.

The results of this analysis are not drastically different from the suggestions put forward by the SAP; however, this analysis follows a clear, defensible, logical and repeatable approach for establishing numeric chlorophyll *a* criteria that are grounded in science and are fully consistent with the conclusions of the SAP's Empirical Relations report. We recommend the use of linear models of geometric monthly mean chlorophyll *a* concentrations and threshold exceedances to empirically evaluate the chlorophyll *a* concentration levels which correspond to 10% impairment associated with the HABs, pH, or water clarity metrics and

50% impairment associated with the PIBI metric. This approach is consistent with Virginia DEQ's current criteria assessment procedures, the CBP Criteria Assessment Procedures Workgroup's proposed chlorophyll *a* criteria assessment procedures as well as EPA's published Chesapeake Bay chlorophyll *a* criteria guidance (U.S. EPA 2003, 2008, 2010).

One concern with this approach, that has been raised previously, is that criteria derivation is based upon multiple metrics which have varying degrees of aquatic life impacts. As a result, these conclusions are highly dependent upon the threshold (i.e. 0.8 ug MC L^{-1}) which is utilized. The SAP did put extensive effort into choosing thresholds that had a strong basis. For instance, in regards to *Cochlodinum* blooms, a literature review was performed inclusive of the assays performed associated with this work and a value close to the median of where >20% mortality occurs was selected. For Microcystin, a threshold was selected which corresponded to the average level where 50% of filtration inhibition was observed. For other metrics—pH and DO—references to published water quality criteria were utilized to justify the thresholds. These decisions do require some level of professional judgement and the SAP report documented the rationale for these choices. The thresholds which were selected certainly have a strong influence on the results of this analysis, and if there are criticisms to the approach taken we encourage further discussion and consideration of these issues. However, these thresholds were not selected arbitrarily by the SAP members but on the basis that they lead to aquatic life impairments.

Furthermore, we suggest that while this approach is sensitive to the magnitude of threshold that is selected, the SAP's approach does not improve the likelihood that this issue is adequately addressed. The SAP's approach was specifically focused upon selecting criteria at the point at which threshold exceedances showed an increase, but the magnitude of this increase was not considered. As a result, increases from low to moderate or low to high or even very low to low were all treated equally. Furthermore, this approach was limited by the lowest observed threshold, and thus would not provide an opportunity to establish a criterion value lower than what was observed over the course of the study. As a result, we feel the approach outlined above provides a stronger choice for criteria derivation. We have tried to partially reconcile this issue by giving priority ranking to those thresholds which are believed to be most problematic and pertinent to chlorophyll *a*.

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