Updated Chlorophyll a Criteria Considerations for High Rock Lake
March 2018

Summary: By looking at several lines of evidence together the chlorophyll a criterion recommendation for High Rock Lake (HRL) is a seasonal arithmetic average (May through October) of 30 µg/L, not to be exceeded more than once in 3 years. As further described in this document, this conclusion is based on information from other comparable reservoir systems, calibrated to reflect known data and model results for HRL, and then closing in the gap with local and more generalized information to account for improved system resilience. As a result, this criterion recommendation reflects:

1) A balanced consideration of all the designated uses of the lake, including a decision to allow a "medium" risk of recreation and drinking water impacts, while not resulting in a chlorophyll a concentration that would be detrimental to the recreational fishing populations,
2) A reduced chlorophyll a concentration designed to lessen super saturated DO conditions and increased pH concentrations typical of a highly eutrophic system, and
3) A provision for resiliency in the aquatic system for future development and/or changing environmental or lake management conditions

Background on Conclusion: Starting from the final recommendation of my June 2017 chlorophyll a document, the duration and magnitude based on comparable geography and reservoir expectation (VA, GA, and AL lakes) chlorophyll a concentrations fell within a range of 5-35 µg/L, as either a 90th percentile of seasonal data or as a growing season average. In preparation for the November 2017 meeting, I looked closer at the designated uses (and corresponding criteria concentrations), for lakes in AL and GA[1], as these states use a seasonal average most similar to the duration being discussed by the North Carolina SAC. The tallied values in the footnote summarize the criterion values for each use or combination of uses for the reservoirs in those two states.

Based on this analysis, the range of criteria concentration values associated with multiple designated use lakes (Swimming (S), Fish and Wildlife (F&W), and Public Water Supply (PWS)), falls within the range of 5-24 µg/L.[2] However, since a model is available for the HRL system, these non-North Carolina values were considered against what are even possible values for HRL based on the modeled data and

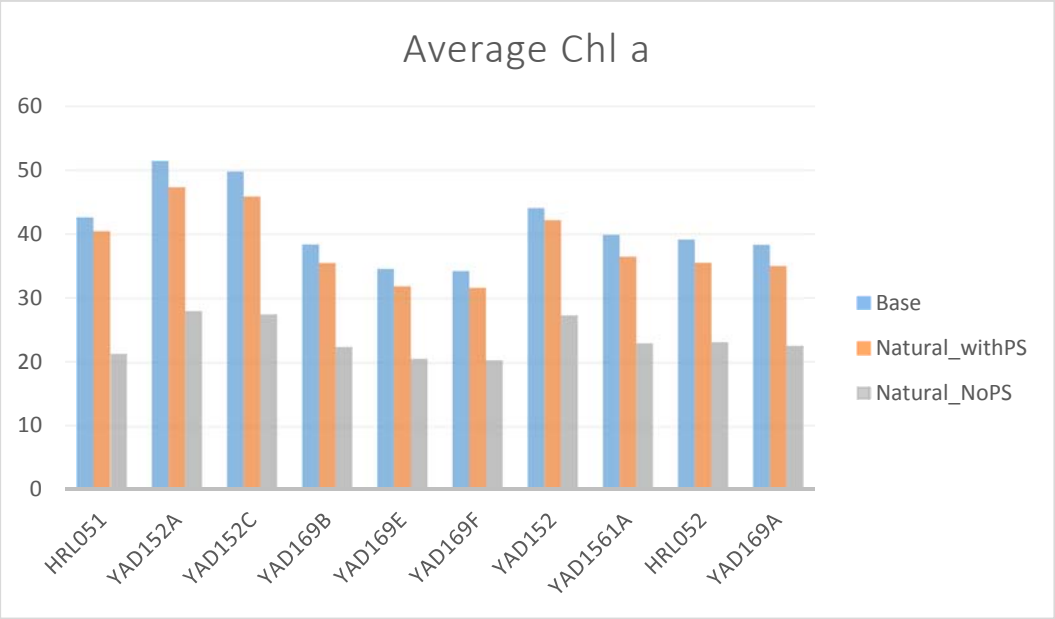
[1] Both Alabama and Georgia use a range of April through October and average the photic zone samples over that time period. Generally speaking each lake is measured at the dam forebay station, but may have additional upstream stations on the mainstem and/or tributaries.

[2]

S, F&W, PWS Or PWS, F&W	AL Lakes: 6,16,8,8,16,8,5,15,14,14/16,17, 17,18,20,10,5,5,5,10/12,18, 18,18,18 GA Lakes: 22/24, 10/12/10/15/14, 5/6/7/10/10 AL Lakes: 16/18, 11 GA Lake: 10/10	Arithmetic Average=12.7, Median=13 Range=5-24 Arithmetic Average =13, Median=11, Range = 10-18
PWS only	AL Lake: 6	
F&W only	AL Lakes: 16,11,12	Arithmetic Average =13, Median=12, Range = 11-16
F&W, S	AL Lakes: 14,18,10,12,16,15,17,15/18, 24,9,7 GA Lakes: 15/18, 20	Arithmetic Average =14.6, Median=15, Range= 7-20

information. Looking at the HRL model, the natural condition scenario without point sources, shown in Figure 1, highlights the fact that chlorophyll a values in the low to mid 20s (as a growing season arithmetic average) are the lowest this lake could even be expected to achieve under natural conditions. The natural condition scenarios are considered forested, with differences of with and without point sources shown for comparison. Therefore, in the case of High Rock Lake, a man-made reservoir, values less than 20 µg/L would not be appropriate based on the available modeling, although these were appropriate for protection of designated uses in other southeastern states, and may be appropriate levels in other North Carolina lakes.

Figure 1. Comparison of Three Modeled Scenarios (as May-October Arithmetic Averages) based on the HRL Model.



With that in mind, for High Rock Lake, we can now limit the lower end of a seasonal chlorophyll a average concentration to 25 µg/L (which captures the variability in the low end values among the stations). So, the next question to answer is: "How much above 25 µg/L is too high to protect the various designated uses of HRL?" While 40 µg/L has been discussed as an upper limit in the past, primarily as reflecting the "original intent" for the criteria, I would highlight that we now have about 40 additional years of data and knowledge on nutrient enrichment that should be considered.

Selecting an appropriate chlorophyll a criterion is critical to ensuring that all designated uses in HRL are protected and ensures the right endpoint, magnitude, and duration for the SAC's eventual recommendations for appropriate total nitrogen (TN) and total phosphorus (TP) criteria. Related to more recent nutrient efforts, one thing that has changed over time is the shift from a historically phosphorus focused management strategy for lakes to one that considers both phosphorus and nitrogen. Additionally, given the amount of development that is happening across North Carolina, the growing knowledge of algal communities, and the difficulty in determining every "switch" which can cause an algal group to create toxins warrants careful consideration to ensure the resulting

recommendation is protective. The following excerpt from Touchette[3] in 2007 highlights the importance of considering for future impacts, particularly those related to drinking water and recreation.

> Overall, this study indicates that at present, these turbid, meso-/eutrophic reservoirs have only moderate cyanobacteria abundance and low cyanotoxin (microcystin) levels, even in the low-precipitation summer growing season analyzed. Nevertheless, the significant relationships between phytoplankton chl*a* and cyanobacterial abundance, and between both parameters and TP, together with the fact that nearly one-fourth of the samples had chl*a* values equal to or in excess of the state standard for acceptable water quality, indicate that when under drought conditions with reduced turbidity and flushing, these reservoirs may respond similarly as natural lakes to nutrient over-enrichment (Dillon and Rigler 1975, Vollenweider 1975, Jones and Bachmann 1976, Hoyer and Jones 1983, Wetzel 2001). **Considering that cyanotoxin production can be stimulated by nutrient enrichment (Zurawell 2005, Gobler *et al.* 2007), these potentially toxic taxa may adversely affect the utility of these impoundments for potable water supplies and recreational activities as eutrophication progresses. (emphasis added)**

In addition to acknowledged development and changes in management strategies in general, a more recent presentation on the specific nutrient loading changes happening in the watershed was provided at the April 2017 CIC meeting. One of the presentations highlighted the fact that the total discharged phosphorus load from point sources was experiencing a decrease. While this is positive news for the potential for reductions of phosphorus loads being delivered to HRL, the presentation also indicated that there appears to be an increase in the discharged total nitrogen load from point sources. This information and any results from the follow up analysis discussed in that April 2017 CIC presentation will be critical for consideration as the SAC moves into development of the causal parameters, TP and TN.

Before getting into the final discussion of the magnitude of this recommendation, which considers resilience and the newer developing science of harmful algal bloom toxins, it is worth quoting the following from University of Virginia's Mike Pace's presentation on determining the early warning signs of resilience loss.[4]

> There may be no advance warning for some kinds of abrupt change, reinforcing the need to enhance resilience by managing ecosystems to reduce the possibility of crossing thresholds of change.

Based on the SAC's November 2017 discussion of designated uses and the ambient water quality and balancing of risk, I hope that the above has summarized the need to consider a recommendation building on the information learned over the more recent history in nutrient criteria development, while being clear that my goal is not to select something that is infeasible due to the fact that this water has been a man-made reservoir for 90 years and counting.

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[3] Touchette, B.W., J.M. Burkholder, E.H. Allen, J.L. Alexander, C.A. Kinder, C. Brownie, J. James and C.H. Britton. 2007. Eutrophication and cyanobacteria blooms in run-of-river impoundments in North Carolina, U.S.A. Lake and Reserv. Manage. 23:179-192.

[4] Mike Pace, with the University of Virginia, has presented his findings in EPA's nutrient webinar series. With and without warning: managing ecosystems in a changing world. Michael L Pace, Stephen R Carpenter, and Jonathan J Cole. Frontiers in Ecology and Environment 2015; 13: 460-467.

With that in mind, although there is limited data on toxins specifically for HRL, it seems it would be useful to consider the existing blue green dominance, cyanobacteria counts, and toxin ranges relative to chlorophyll a concentrations that we have been provided to date. In Table 1, I have sorted the information into three categories of risk: low, medium, high. Given the knowledge that we have of High Rock Lake's current conditions, combined with the more widely listed values of other sources, I am making the assumption that the information contained in the medium risk category description below represents the best approximation of what would be considered a protective chlorophyll a concentration for High Rock Lake.

Instead of picking a percentile of the values, I chose to weight the ends of the provided ranges equally, given the difficulty in otherwise weighing a mix of qualitative and quantitative outcomes. The thought is that within the medium risk category this average represents a desired instantaneous condition to be met with some regularity. Instead of making the criterion an instantaneous value, as has been the case historically, this value is intended to further support a final magnitude recommendation of 30 µg/L as a seasonal arithmetic average. Selecting an average criterion recommendation of 30 µg/L also considers there will be some months that may be higher or lower than the values listed in the medium risk category, but with an expectation for achieving an overall average that relates to this medium risk level concentration.

Table 1. Summary of Risk Level Category Information.

Risk Level Category	Data/Information Source	Resulting Arithmetic Average of Given Chlorophyll Values
Low Risk	1) Jing Lin's ppt from August 2015 SAC meeting: instantaneous chlorophyll a concentrations <30 µg/L represented mild or less blooms and corresponded to 9.3% blue green dominance. 2) Bill Hall's ppt from April 2016 SAC meeting: chlorophyll concentrations of 9-10 µg/L associated with drinking water taste and odor problems and low probability of adverse health effects 3) WHO Guidance Values[5]: Low relative probability of acute health effects (<20,000 cells/mL, < 10 µg/L Microcystin-LR) associated with chlorophyll a <10 µg/L	16.5 µg/L
Medium Risk	1) Jing Lin's ppt from August 2015 SAC meeting: instantaneous chlorophyll a concentrations of 30-40 µg/L represented moderate to severe blooms and corresponded to 46.4% blue green dominance. 2) Bill Hall's ppt from April 2016 SAC meeting: chlorophyll concentrations of 30 and 50 µg/L associated with increased risk of algae related health problems and moderate risk of health effects	30.6 µg/L

[5] https://www.epa.gov/nutrient-policy-data/guidelines-and-recommendations#what3 The WHO guidance values for the relative probability of acute health effects during recreational exposure to cyanobacteria and the probability of microcystins concentrations are given at this site.

	3) Bill Hall's ppt from April 2016 SAC meeting: chlorophyll concentrations of 15-20 µg/L associated with water supply use impairment 4) WHO Guidance Values: Moderate relative probability of acute health effects (20,000-100,000 cells/mL, 10-20 µg/L Microcystin-LR) associated with chlorophyll a 10-50 µg/L	
High Risk	1) Jing Lin's ppt from August 2015 SAC meeting: instantaneous chlorophyll a concentrations >40 µg/L represented mild or less blooms and corresponded to 61.5% blue green dominance. 2) Bill Hall's ppt from April 2016 SAC meeting: chlorophyll concentrations of 20-80 µg/L associated with severely impaired consumptive uses 3) WHO Guidance Values: High relative probability of acute health effects (100,000-10,000,000 cells/mL, 20-2,000 µg/L Microcystin-LR) associated with chlorophyll a 50-5,000 µg/L 4) WHO Guidance Values: Very high relative probability of acute health effects (>10,000,000 cells/mL, >2,000 µg/L Microcystin-LR) associated with chlorophyll a >5,000 µg/L	~1,700 or *47.5 µg/L

*Based on removing the values of 5,000 from averaging as these are not typical for HRL.

With regard to the decision on arithmetic average versus geometric means, most of the data points used in this paper to support the conclusion of a 30 µg/L are based on arithmetic averages not geometric means. In order to further analyze the differences, if any, between the arithmetic average and geometric mean, the historical data was considered. Table 2 summarizes the HRL data from years with more than a single month of data within the growing season to show the observed arithmetic average and geometric mean. The values are lumped by year and include four to 11 stations depending on the year. The years 2006 and 2011 had both good spatial coverage (11 stations) and higher sample size (n = 55 - 66) and are described further below.

In general, Table 2 illustrates, for both the arithmetic averages and geometric means, there is an observed increase in concentrations over time, and to some degree, an increase in the range of values. The earlier data appears to show values similar to those found in the modeling analysis. Further analysis of the most robust years 2006 and 2011 indicate that the distributions were relatively normal and therefore, use of either the arithmetic or geometric mean would be appropriate. If the SAC were to determine that a geometric mean was preferred, then this write up would need to be modified to reflect the shift in statistic used so that the magnitude is appropriately derived for the given duration.

Table 2. Summary of Arithmetic Averages, Geometric Means, and Ranges in Years with Multi-Month Data.

Year	Arithmetic Average of Growing Season Data (in µg/L)	Geometric Mean of Growing Season Data (in µg/L)	Range of Single Values (in µg/L)	Notes
1982	25.6	15.5	2-45	June, July (n=14)
1990	21.9	18.1	4-41	May-Sept (n=20)
2001	38.4	25.5	3-52	July-Aug (n=15)
2002	37.6	26.6	0.5-61	June, July, Sept (n=20)
2004	34.4	31.1	3-53	June, July, Aug (n=23)
2005	39.4	35.8	13-71	April, Oct (n=20)
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2006	41.6	39.5	12-71	April-Sept (n=66)
	42.3	40.0	12-71	May-Sept (n=55)
2008	39.9	38.5	17-52	April – Oct (n=10)
	42.4	42.2	33-52	May-Oct (n=9)
2009	29.2	26.1	14-54	May-July, Sept (n=5)
2011	44.7	40.9	13-86	May, July-Sept (n=55)

NOTE: Data from years 1981, 1983, 1984, 1985, 1986, 1989, 1994, and 2010 were not used because there was either no or only single month data in the growing season months.
**Data from 2005 includes only October samples, once April is removed for purposes of computing averages, so it is not shown here for the same reasons others years were not included.*

With regard to the frequency, the use of a 1-in-3 allowable excursion frequency is an established approach and is consistent with EPA's recommendations when protecting aquatic life against long-term effects.

Finally, from a regulatory perspective, in the end, if there are concerns relating to future application of any recommendation the SAC puts forward, I would caution that there are two places these questions should be addressed, by the SAC, CIC, and/or the State. There are certain implementation type things to be considered in criteria development, like duration and frequency, that address how the criteria will be protective of the designated uses of the lake. Variability is also something that should be considered, to a degree. These technical pieces of the criteria should be the focus of the SAC. In contrast, sampling frequencies, future monitoring considerations, every condition related to variability, etc., while useful to understand, can be discussed in greater detail, once a criterion is recommended, as these details should not have an influence on the criterion development itself.