

EVALUATING THE ASSESSMENT METHODOLOGY FOR THE CHLOROPHYLL-A AND
SECCHI TRANSPARENCY CRITERIA AT BEAVER LAKE, ARKANSAS

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Introduction

The U.S. Environmental Protection Agency (EPA) has called on states to develop nutrient criteria or numeric translators for narrative criteria for all water bodies that would be protective of designated beneficial uses. The EPA (2010) recommended a weight of evidence approach to develop numeric criteria, based on reference conditions, mechanistic modeling or stressor-response analysis. State adoption of numeric criteria have been slow, and most states have used stressor-response analysis as the primary source of information to derive criteria. In fact, many states have set numeric criteria for the response variable (e.g., chlorophyll-a [chl-a]), essentially managing nutrients with an effects-based approach.

The total phosphorus (TP) and chl-a relationship was first established for northern temperate lakes and shows that phytoplankton biomass measured as chl-a increased proportionally to TP (Dillon and Rigler 1974). This model has been widely applied in lake and reservoir management to identify P reductions necessary to achieve chl-a water quality targets (Cooke et al. 2005), and has been coupled to secchi transparency (ST) to provide another effects-based assessment of water quality (Carlson 1977). As such, twenty-two states have adopted chl-a criteria on a statewide, regional, or site-specific basis (EPA 2014 web site). Each of these chl-a standards are associated with a specific assessment method, including sampling frequency, depth, and location. The mean or median of chl-a concentrations during the growing season measured near the surface and at the deepest point in the water body has been the most common assessment method adopted by states (Table 1). The chl-a criteria across these states ranged from 1.5 to 27 $\mu\text{g/L}$ and were site-specific (reservoir or geographic location) or specific to a designated beneficial use, i.e. domestic water supply.

Variation in the chl-a criteria among states occurs because there are different water quality goals for states, regions, and individual waterbodies. Further, there is regional variability in the non-linear TP–chl-a relationships (Filstrup et al. 2014), as well as difference in the distribution of chl-a concentrations across eco-regions (Herlihy et al. 2013). Recent work has demonstrated that lakes and reservoirs can be classified based upon biological, chemical and physical attributes to further improve the relation between nutrients and chl-a for regional standards (Yuan and Pollard, 2014). However, depending on the scale of the regional groupings, the chl-a and TP relationship may be robust and Jones et al. (2011) suggested the increase in chl-a with TP was similar across Missouri reservoirs.

From a human health perspective, there is a need to link nutrients, algae, organic carbon, and disinfection by-products (DBP) or cyano-toxins when establishing numeric criteria for chl-a (Yuan et al. 2013). Callinan et al. (2013) suggested that a mean chl-a threshold between 4 and 6 $\mu\text{g/L}$ would be protective of water supply lakes and reservoirs in New York, with regard to the production of DBPs. However, other work has shown that DBP formation potential increases only mildly as chl-a increases over orders of magnitude due to eutrophication (Mash et al. 2014). Instead, DBP formation potential was more strongly influenced by seasonal variation in dissolved organic carbon (DOC) concentrations. The production of the cyano-toxin Microcystin has been linked to elevated phytoplankton biomass measured as chl-a, as well as the nitrogen (N) and P concentrations that drive these biomass increases across lakes (Scott et al. 2013). Yuan et al. (2014) used the frequency of occurrence of high Microcystin concentration to identify chl-a thresholds that ranged from 1-14 $\mu\text{g/L}$. There is a great need to extend stressor-response to these specific water quality outcomes that directly influence the capacity of waterbodies to support their designated beneficial uses. However, these standards must also link back to basic nutrient

concentrations with a defined measurement frequency and duration in order to inform watershed management.

Effects-Based Water Quality Criteria in Beaver Lake, Arkansas

The State of Arkansas recently adopted its first effects-based water-quality criteria related to nutrients. A site specific chl-a and ST standard were adopted for Beaver Lake in Northwest Arkansas (APCEC 2012). According to State of Arkansas Regulation Number 2, which is the state regulation defining water quality standards (APCEC 2012), the growing season (May – October) geometric mean chl-a concentration in Beaver Lake near Hickory Creek shall not exceed 8 µg/L and the annual average ST shall not be less than 1.1 m. The standards were adopted from the recommendations of a working group that conducted a multi-tiered analysis (FTN 2008). The basis for choosing the 8 µg/L chl-a standard and the 1.1 m ST standard came from a weight of evidence approach and included the following six specific considerations (from FTN 2008, Section 9.3):

1. Chl-a and ST criteria adopted into regulation or recommended for adoption in surrounding states
2. Ecoregional values published by the EPA
3. Percentile values for reference lakes and extant values for Beaver Lake
4. Statistical analysis of Beaver Lake and reference lake data
5. Empirical nutrient loading relationships
6. Dynamic modeling results

The recommended standards for both chl-a and ST were derived to protect the designated uses of Beaver Lake, which include its role as a drinking water source to Northwest Arkansas (FTN

2008). However, it is also clear that the standards recommended in the report and ultimately adopted by the State of Arkansas represent an expected average condition at the Hickory Creek location in Beaver Lake. This is supported by the following quotation borrowed from Section 9.3 of the standard development report (FTN 2008):

“The chlorophyll regression equation was used to estimate concentrations at Lowell, and subsequently at the Hickory Creek site by averaging the values from the Highway 412 and Lowell sites. The Hickory Creek site is located about half the way between Highway 412 and Lowell. A growing season geometric mean chlorophyll concentration of 10 and 12 µg/L at Highway 412 results in a predicted geometric chlorophyll mean of 4.5 and 4.8 µg/L at Lowell, with the upper 95% geometric means at Lowell estimated as 6.5 and 6.9 µg/L, respectively. The associated Hickory Creek growing season geometric chlorophyll means estimated for the Hickory Creek site were 7.5 and 8.5 µg/L, respectively. The DeGray reference lake chlorophyll concentration was 9 µg/L, which is consistent with this estimated value.”

Although it is not obvious why the exact “10 to 12” µg/L chl-a was used for the Highway 412 location in the above quotation, those values are in the same range as promulgated chl-a criteria in other states (Table 1). However, the criteria in those states typically applies to the deepest location in the lake near the outfall or dam. The Highway 412 location in Beaver Lake is immediately below the input of the White River, which is almost 50 km from the dam. The range of chl-a reported for the Highway 412 location throughout the standard development document was 5.2 to 32.6 µg/L (FTN 2008). This reported range included geometric means for different observation periods and from empirical and dynamic modeling activities. The application of this

average condition as shown above quotation demonstrates that the average expected chl-a concentration in Beaver Lake at Hickory Creek is approximately 7.5 to 8.5 µg/L. Thus, the adopted 8 µg/L is practically equivalent to the long-term expected average condition at Hickory Creek. A similar methodology was used to derive the 1.1 m ST standard, and numerous references throughout the standard development document indicate that the long-term expected condition at Hickory Creek was approximated by this value (FTN 2008).

The intent of the standard development activities reported by FTN (2008) was clearly to identify values of chl-a and ST that when exceeded would result in a failure of Beaver Lake to meet its designated uses. This range of values is similar to other standards in neighboring states and are supported by the scientific literature discussed previously. However, the standards recommended and ultimately adopted were not expected to result in Beaver Lake being immediately listed on the Arkansas 303d list of impaired water bodies. This is clear from the following quotation borrowed from Section 9.4.2. – Rationale for Criteria in standard development document (FTN 2008):

“The chlorophyll and Secchi transparency mean values are considered conservative and protective of the designated uses, but should not result in frequent non-attainment assessments.”

Thus, the approximate average expected conditions of 8 µg/L chl-a and 1.1 m ST at the Hickory Creek location in Beaver Lake were not expected to result in frequent violations.

A substantial missing component of the standard development document (FTN 2008) was the derivation of an assessment criteria that defines the allowable frequency and duration of exceedance of the water quality standards. A common assessment methodology used in surface

water assessment by the State of Arkansas is to allow no more than one violation in a five year assessment period (ADEQ personal communication, 2014). The adoption of this method for the Beaver Lake chl-a and ST standards would very obviously result in a water quality violation because the standards were equivalent to a long-term expected average condition in Beaver Lake at Hickory Creek. Thus, assuming the data have a normal distribution, the standards should be expected to be exceeded in approximately half of the years in an assessment period. It is therefore important to create an assessment methodology which is consistent with the information used to develop the water quality standards for Beaver Lake. As written in the standard development document, the standards should be protective of designated uses, but not result in frequent non-attainment if chl-a concentrations and ST does not vary from its long-term expected condition at Hickory Creek.

Study Objectives

Although the chl-a and ST developed for Beaver Lake were specifically intended to apply to the location near Hickory Creek, no historic data were available for that site. As alluded to above, a regression relationship demonstrated that the selected standards were approximately equivalent to the long-term expected average conditions for Beaver Lake at Hickory Creek. Since the time of standard development, six years of assessment data have been collected at the Hickory Creek location. In addition, similar data have been collected at several other locations in the lake using the same sampling and analysis methodologies.

The objective of this study was to derive an initial assessment methodology based on the method(s) used to develop the site-specific numeric criteria for chl-a and ST in Beaver Lake at Hickory Creek. In order to accomplish this, we evaluated the probability of exceeding the

promulgated criteria, based on the data publicly available through the U.S. geological Survey (USGS) National Water Information System (NIWS). We explicitly evaluated the risk of exceeding the 8 µg/L chl-a standard and the 1.1 m ST standard using data collected in Beaver Lake since 2001 because those data were collected using standardized techniques that were replicated through the entire period of record. This analysis provided specific expectations about the number of violations of the adopted water quality standards that should be expected based on an allowable level of risk (10%-20%), which was consistent with the acceptable risk presented in the standard development document (FTN 2008). We also evaluated Beaver Lake chl-a, ST, and TP data relative to common limnological models that are often used in water quality assessment in order to provide context regarding potential assessment methodologies.

Methods

Study Site and Data Description

Beaver Lake is a large multi-use reservoir of the U.S. Army Corps of Engineers on the White River in Arkansas, and it is the most upstream reservoir on the river system; the downstream USACE reservoirs include Table Rock Lake and Bull Shoals Lake within the White River Basin. This reservoir has been authorized for flood control, hydroelectric power generation, and domestic and industrial water supply (USACE, 1998), and the reservoir is also used for recreation and fish and wildlife management. Beaver Lake is the water supply for northwest Arkansas, providing domestic water supply to approximately 400,000 citizens and multiple industries, including poultry processing facilities. There are currently four public water suppliers using the reservoir, and the most upstream is the Beaver Water District (BWD). The water-quality standards, i.e. geometric mean chl-a concentration and annual arithmetic average

ST criteria, were developed to protect the reservoir from a drinking water perspective, but the other uses were also considered (FTN 2008).

Beaver Lake and its tributaries were monitored routinely for water quality by numerous agencies, including the Arkansas Department of Environmental Quality (ADEQ), Arkansas Water Resources Center (AWRC), BWD, and the U.S. Geological Survey (USGS). The USGS collects water samples from Beaver Lake at five locations (Figure 1), Highway 412, Hickory Creek, Lowell, Highway 12, and then the dam (from upstream to downstream, respectively). The USGS measures ST and collects water samples at these locations from three depths, including approximately 2 m below the surface, the metalimnion near the thermocline, and in the hypolimnion above the sediment-water interface. The water samples are collected from Beaver Lake and then transported to the USGS National Water Quality Lab, where each water sample is analyzed for TP, chl-a, and other typical water-quality constituents. Secchi transparency was measured and water samples collected approximately 6-8 times per year on average, and the frequency of collection is greater during the growing season (defined as May through October).

The USGS database was used in this study to quantify the probability of exceeding the State of Arkansas numeric criteria for Beaver Lake, and in the evaluation of the assessment methodology from calendar year (CY) 2001 through 2014. Only one sampling depth (~2 m below the surface) was used to calculate geometric mean concentration of chl-a at each site during the growing season (May through October) of each CY, and the arithmetic average of all ST measurements within a CY was used. The water quality standard is currently assessed using data from Hickory, as defined by Arkansas Regulation Number 2 (APCEC 2012). However, water sampling at Hickory Creek (by the USGS) only began in CY 2009 – thus, data was not available at the point of potential regulation during the development of the chl-a and ST criteria.

All data used in this study are publicly available through the USGS National Water Information System (NWIS, <http://waterdata.usgs.gov/nwis>). ADEQ does not have specific guidelines on the number of allowable exceedances of water quality criteria. However, ADEQ does often apply a threshold of two or more exceedances in a five year assessment as evidence of impairment because this would represent a 40% loss of use (ADEQ personal communication, 2014).

Predicted Data

Because data at Hickory Creek was only available for CY 2009 through 2014, this would provide only 6 geometric mean chl-a and arithmetic average ST from which to estimate probabilities of exceeding the defined criteria. Therefore, we had to predict values for chl-a and ST at Hickory Creek based on available data at the other sites, particularly the sites upstream (HWY 412) and downstream (Lowell). The document (FTN 2008) that developed the implemented criteria was used to provide guidance on how we predicted values at Hickory Creek, keeping our techniques similar to that used in criteria development. By predicting values at Hickory Creek, this allowed us to create a database where we have 14 years of predicted values of geometric mean chl-a concentration during the growing season and annual arithmetic average ST to evaluate the probability of exceeding the criteria.

In order to derive expected values for Hickory Creek, we utilized measured data from 2009-2014 to determine if there was a statistically significant relationship between chl-a at Highway 412 and Hickory Creek or between chl-a at Lowell and Hickory Creek. No such relationship was apparent from the data. Thus, we employed the method used in the standard development (FTN 2008) in which the relation between geometric mean chl-a concentration at Highway 412 and Lowell to predict this response variable at Hickory Creek with data from 2001

through 2014. Simple linear regression was used to develop a relation a predictive equation between the geometric mean concentration of chl-a at Highway 412 and Lowell ($\text{chl-a}_{\text{Lowell}} = 0.3174 \cdot \text{chl-a}_{412} + 2.385$, $R^2=0.40$, $p=0.02$). This equation was used to predict values at Lowell based on the observed geometric mean chl-a at Highway 412. The predicted geomean chl-a concentrations for Lowell were averaged with the measured geometric means at Highway 412 to estimate values for Hickory Creek. This technique was replicated from the method used in the standard development (FTN 2008). We recognize that these values at Hickory Creek are predicted, and that caution should be used in the interpretation of the probability of exceeding the chl-a criteria at this site.

The development of expected ST data for Hickory Creek followed the same method. Briefly, we utilized measured data from 2009-2014 to determine if there was a statistically significant relationship between chl-a at Highway 412 and Hickory Creek or between chl-a at Lowell and Hickory Creek. Indeed, a strong relationship between the annual average ST at Lowell and the annual average ST at Hickory creek ($\text{ST}_{\text{Hickory}} = 0.5020 \cdot \text{ST}_{\text{Lowell}} + 0.4436$, $R^2=0.75$, $p=0.03$). This prediction model was then used to estimate the annual average ST for years in which ST measured values were not available for Hickory Creek.

Probability of Exceeding Criteria

The hydrologic frequency method was used to measure the probability that the water-quality standard (i.e., criteria) would be exceeded. Our main assumption here is that the occurrence of each event or measurement against the criteria (i.e., geometric mean chl-a from May through October and annual arithmetic average ST) is a random stochastic process. The probability of a particular criteria being exceeded in any year is P_T , and this probability is

independent and specifically not dependent on previous measurement against the criteria or the history of chl-a and ST in Beaver Lake. Assuming that exceeding the criteria was a Bernoulli random variable and based on a binomial distribution, we can calculate the probability of K occurrences or measurements exceeding the criteria in N years:

$$f(K; P_T, N) = \frac{N!}{(N-K)!K!} P_T^K (1 - P_T)^{N-K}$$

where $f(K; P_T, N)$ is the probability of exactly K occurrences of a measurement exceeding the criteria in N years, if P_T is the probability of an exceedance in any single year (Haan et al. 1994). For example, we can calculate the probability of the criteria being exceeded exactly two times ($K = 2$) in a five year period ($N=5$). We essentially used this equation to calculate the entire spectrum of K over N years, such that in a 5 year period we would have to estimate the probability of exactly 0, 1, 2, 3, 4 and 5 events, where the criteria would be exceeded within the period. The probabilities of 2, 3, 4 and 5 exceedances are then summed to represent the probability of seeing two or more measurements that would exceed the criteria. These calculations were made for both geometric mean chl-a during the growing season (May through October) and the annual arithmetic average of the ST at Beaver Lake.

The above equation requires that we estimate the probability of the criteria being exceeded within any given single year, i.e. P_T . This requires that we use the available data (i.e., geomean chl-a concentration and annual average STs) from the U.S. Geological Survey, and we used the reduced equation representing many types of hydrologic frequency analysis (from Haan et al. 1994):

$$X_T = \bar{X} (1 + C_v K_T)$$

where X_T is criteria of interest, \bar{X} is the mean of the available data (i.e., the mean of the geometric mean chl-a concentrations during the growing season for each individual year or the

mean of the arithmetic average for ST for each individual year), C_V is the coefficient of variation of the available data (i.e., standard deviation divided by the mean), and K_T is a coefficient that is a function of the probability distribution selected.

In this case, we selected the normal distribution because the skewness of the data available from the water supply intake at Beaver Lake was near zero, suggesting that we could use the standardized Z scores or values from the standardized cumulative normal distribution. X_T , C_V and \bar{X} are known variables, so the equation was solved for K_T which was then used to look up the corresponding Z score (Appendix 2, Haan et al. 1994) and estimate the probability of the criteria being exceeded in any given year, i.e. P_T . The inverse of P_T can be used to represent the return interval (i.e., T-year event) for the criteria at each individual sampling site within Beaver Lake:

$$P_T = \frac{1}{T}$$

A T-year event can be thought as the average time between events that have a magnitude greater than X_T – of course, this would be over a long period of time and much longer than the available period of data for Beaver Lake. We used this concept to give an idea of how frequently we might expect the criteria to be exceeded at each individual monitoring site across Beaver Lake. We provide a probability analysis of exceeding the criteria for three time periods, including (1) 2001 through 2008, representing the time period used to develop the criteria and produce the final report (FTN 2008), (2) 2001 through 2014, representing recent, continuous data available through present day, and (3) data collected from 2009-2014 for which measured data were actually available at the Hickory Creek location. The reality is that the longer the time period the better in hydrologic frequency analysis, assuming that the distribution of the values is stationary

over time – that is, not changing due to some anthropogenic or climatic factor which has changed over time.

Results

The gradient in TP concentrations, chl-a concentrations, and ST in Beaver Lake conformed to common limnological models (Figure 2). Consistent with typical patterns in reservoirs, average growing season total P was greatest at the Highway 412 location and least at the dam location. Average growing season TP and chl-a were strongly correlated across all sampling locations ($R^2 = 0.96$, $p = 0.0030$). Similarly, chl-a concentrations were strongly correlated with growing season ST ($R^2 = 0.80$, $p = 0.0412$).

Growing season geometric mean chl-a concentrations ranged from 0.9 $\mu\text{g/L}$ in 2003 at the dam location to 18.8 in 2012 at the Highway 412 location (Table 2). As expected, geometric mean chl-a was generally greatest in the riverine zone of the reservoir and gradually decreased along the riverine-transition-lacustrine gradient. For example, the arithmetic average of the long-term growing season geometric mean chl-a decreased by 0.4 $\mu\text{g/L}$ for each km downstream of the Highway 412 location. Measured geometric mean chl-a concentrations at the Hickory Creek location ranged from 7.0 to 12.3 $\mu\text{g/L}$ and was similar in range to the predicted values for the same period of time (5.8 to 13.6 $\mu\text{g/L}$), which were derived from the regression modeling technique.

Annual average ST ranged from 6.6 m in 2007 at the dam location to 0.4 m in 2010 at the Highway 412 location (Table 3). As expected, annual average ST was generally least in the riverine zone of the reservoir and gradually increased along the riverine-transition-lacustrine gradient. For example, the arithmetic average of the long-term annual average ST increased by

0.05 m for each km downstream of the Highway 412 location. Measured annual average ST at the Hickory Creek location ranged from 1.0 to 1.2 m, which was the same range of values predicted from the regression modeling technique over the same period of time (0.9 – 1.2 m).

Growing season geometric mean chl-a concentrations were increasing by $0.29 \mu\text{g L}^{-1}$ year⁻¹ at Lowell ($R^2 = 0.30$; $p = 0.0440$) from 2001-2014 (Figure 3a). Average annual ST was decreasing by 0.05 m/year at Lowell ($R^2 = 0.41$; $p = 0.0143$) from 2001-2014 (Figure 3b). There was no statistically significant trends in growing season geometric mean chl-a concentrations or annual average ST at Highway 412 (chl-a: $R^2 = 0.20$, $p = 0.1046$; ST: $R^2 = 0.20$, $p = 0.1145$), Highway 12 (chl-a: $R^2 = 0.05$, $p = 0.4552$; ST: $R^2 = 0.13$, $p = 0.2065$), or at the dam (chl-a: $R^2 = 0.06$, $p = 0.4133$; ST: $R^2 = 0.02$, $p = 0.6547$). There was insufficient data to evaluate any long-term trends in these parameters at the Hickory Creek location.

The probability of the growing season geometric mean chl-a exceeding $8 \mu\text{g/L}$ or annual average ST exceeding 1.1 m in two or more years of a five year assessment period differed across sampling locations and between the different data sets (2001-2008 vs. 2001-2014 vs. 2009-2014) used for the analysis (Figure 4). There was a near 100% probability that the growing season geometric mean chl-a concentration would exceed $8 \mu\text{g/L}$ in two or more years of a five year assessment period at the Highway 412 location, regardless of which data set was used (Figure 4a). This probability dropped to approximately 40% at the Hickory Creek location when using data collected between 2001-2008. However, there was greater than 90% probability that two or more growing season geometric mean chl-a concentrations would exceed $8 \mu\text{g/L}$ at Hickory Creek in the five year assessment period when using data from 2001-2014 or 2009-2014 (Figure 4a). For the Lowell location, these probabilities dropped to < 5%, 20%, and 70% for the 2001-2008, 2001-2014, and 2009-2014 data sets, respectively. There was < 1% probability that

the growing season geometric mean chl-a concentration would exceed 8 µg/L two or more times in a five year assessment period for samples collected at Highway 12 or further downstream in the lake. These results are consistent with the spatial pattern in chl-a concentrations. The average of growing season geometric mean chl-a concentrations from 2009-2014 decreased from upstream to downstream, and the 8 µg/L target occurred approximately 20 km downstream of Highway 412, which corresponds closely with the Lowell sampling location (Figure 4b).

There was a near 100% probability that the annual average ST would exceed 1.1 m in two or more years of a five year assessment period at the Highway 412 location regardless of which data set was used (Figure 4c). This probability dropped to approximately 10%, 40%, or 90% at the Hickory Creek location when using data collected between 2001-2008, 2001-2014, or 2009-2014, respectively. The probability of exceeding the annual average ST criteria at Lowell was 20% or less for all data sets (Figure 4c). There was < 1% chance that the annual average ST would exceed 1.1 m two or more times in a five year assessment period for samples collected at Highway 12 or further downstream in the lake. These results are consistent with the spatial pattern in ST. The average of annual average ST from 2009-2014 increased from upstream to downstream, and the 1.1 m target occurred approximately 15 km downstream of Highway 412, which corresponds closely with the Hickory Creek sampling location (Figure 4d).

In general, as the assessment period was increased from the three to ten years, the probability of observing values greater than the 8 µg/L growing season geometric mean (Figure 5) or the 1.1 m annual average ST (Figure 6) also increased. The probability of observing exceedances in both standards across all sampling locations was greater in the 2009-2014 data set compared to the 2001-2008 data set (Figures 5 and 6). As a result, 2001-2014 data had exceedance probabilities that reflect this variability. Increasing the number of required

exceedances in any assessment period always decreases the probability of exceeding the standards. For example, there was a greater than 90% chance of exceeding the chl-a standard twice or more in five years at the Hickory Creek location using the 2001-2014 data set (Figure 5e). However, this probability decreased to approximately 60%, 30%, and 10% as the number of exceedances for a five year assessment period were increased to three or more, four or more, or five, respectively (Figure 5e).

A 20% probability threshold was used in order to compare the various assessment periods and exceedance frequencies among data sets and monitoring locations for both the chl-a and ST standards. The probability of exceeding the 8 $\mu\text{g/L}$ growing season geometric mean chl-a at Highway 412 was always greater than 20% (Figure 5 a-c) except when using an exceedance minimum of four or more years across an assessment period of four or more years, respectively (Figure 5a). There was a 20% probability that three in six growing season geometric mean chl-a concentrations would exceed 8 $\mu\text{g/L}$ at Hickory Creek in the 2001-2008 data set (Figure 5d). When using the 2001-2014 data set, there was a 20% probability than five in six growing season geometric mean chl-a concentrations would exceed 8 $\mu\text{g/L}$ at Hickory Creek (Figure 5e). Six of six samples met the 20% probability threshold at the Hickory Creek location with the 2009-2014 data set (Figure 5g). At Lowell, there was never greater than 20% probability of exceeding the chl-a standard using the 2001-2008 data set (Figure 5g). However, the 2001-2014 data showed a 20% probability of exceeding the chl-a standard two or more times in five years (Figure 5h). There was a 20% probability of having four of six growing season geometric mean chl-a exceed 8 $\mu\text{g/L}$ at Lowell with the 2009-2014 data set (Figure 5i). The probability of exceeding the chl-a standard at the Highway 12 location never exceeded 20%, regardless of data set, exceedance frequency, or assessment period (Figure 5j-l).

The probability of exceeding the 1.1 annual average ST at Highway 412 was always greater than 20% regardless of data set, exceedance frequency, or assessment period (Figure 6a-c). There was a 20% probability that two in seven annual average STs would exceed 1.1 m in the 2001-2008 data set for Hickory Creek (Figure 6d). However, there was an approximate 20% probability that two in three or three in six annual average STs would exceed 1.1 m in the 2001-2014 data set for Hickory Creek (Figure 6e). Furthermore, the probabilities of exceeding 1m greatly increased when using the 2009-2014 data set, where there was a 20% probability that three in three exceedances would occur (Figure 6f). At Lowell, there was never greater than 20% probability of exceeding the ST standard using the 2001-2008 data set (Figure 6g). However, the 2001-2014 data showed a 20% probability of exceeding the ST standard two or more times in seven years (Figure 6h) and the 2009-2014 data showed a 20% probability of of two or more exceedances in five years (Figure 6i). The probability of exceeding the ST standard at the Highway 12 location never exceeded 20%, regardless of data set, exceedance frequency, or assessment period (Figure 6j-l).

Discussion

The objective of this study was to derive an initial assessment methodology based on the method(s) used to develop the site-specific numeric criteria for chl-a and ST in Beaver Lake at Hickory Creek. Our intention was to provide information for the regulatory agencies and stakeholders on options for assessing the promulgated criteria as currently written in Arkansas Regulation No. 2 (APCEC 2012), because the numeric criteria were not originally linked to an assessment method. In order to meet these objectives, we used the original standard development document, and our own analysis of data collected in Beaver Lake since 2001 to re-create the

work done in the standard development, to derive a single assessment methodology recommendation. We also offer several other assessment options for consideration.

Assessment Methodology Recommendation and Justification

Assessment Methodology Recommendation - *The minimum number of exceedances that trigger a water-quality violation should be greater than one-half the number of years in the assessment period.*

The chl-a and ST standards for Beaver Lake at Hickory Creek were developed to protect the drinking water designated use of Beaver Lake at a location above all water utility intakes (FTN 2008). Although the standards were developed from a weight of evidence approach, the recommended standards were also effectively equivalent to the expected long-term average conditions in Beaver Lake at Hickory Creek. Thus, at least half of the growing season geometric mean chl-a values and annual average ST values in an assessment period should be expected to exceed these criteria. This assumes that the long-term geometric mean chl-a and annual average ST are normally distributed with equal errors, which is supported by our analysis.

Given that the number of violations should be greater than or equal to one-half the number of years in an assessment period, it seems logical that the assessment period should be an odd number of years. In Table 4, we offer the expected number of years in which chl-a and ST data should be expected to exceed the water quality standards based an allowable risk of 10% or 20%, across several options for odd-numbered assessment periods. The 2001-2008 data represent the conditions measured in Beaver Lake prior to the recommendation of the water quality standards and show that approximately half of the growing season geometric mean chl-a would be greater than 8 µg/L over any assessment period, regardless of whether a 10% or 20%

allowable risk is used. These results are similar to the range of acceptable risks quantified in the original standard development document for chl-a at the Lowell location (12% - 18% risk, FTN 2008). When the entire 2001 – 2014 dataset was used, virtually all of the geometric mean chl-a are expected to exceed the standard in a five-year assessment and as many as nine exceedances are expected in an eleven-year assessment, regardless of the 10% or 20% risk level. A similar pattern was apparent for ST violations, but the number of years in violation were slightly less across all options.

The substantially greater number of expected violations that occur when using the 2001 – 2014 dataset indicate that chl-a and ST values in Beaver Lake have changed in recent years. Although detecting those trends and causes was beyond the scope of this study, it is important to note that using the recommended minimum number of exceedances for any assessment period (3 out of 5 years, 4 out of 7 years, 5 out of 9 years, or 6 out of 11 years) will likely result in a water quality violation. The apparent increase in chl-a and decrease in ST identified in this study may well indeed indicate that water quality has deteriorated in Beaver Lake since 2008. Thus, selecting the recommended minimum allowable exceedances would likely result in a listing that was justified.

Another consideration in choosing an assessment methodology is determining whether or not the lake is actually supporting its drinking water supply designated use. This can be defined as whether or not municipal water providers have been able to meet their drinking water standards using conventional treatment processes. Beaver Water District, the major water utility using Beaver Lake as a raw water source, has not violated drinking water standards during this time (BWD personal communication, 2014). However, BWD adopted a non-conventional treatment technique, in order to address stage 2 treatment criteria for the DBP total

trihalomethanes (TTHM) that were implemented in 2013. BWD added chlorine dioxide as a pre-treatment oxidant in order to decrease TTHM levels in their distribution system, and the use of this non-conventional treatment decreased TTHM levels. If this treatment option had not been added, TTHM levels would likely not be in compliance with the stage 2 treatment criteria adopted in 2013 (BWD personal communication, 2014).

A recent study also examined how eutrophication may affect TTHMs during the treatment of Beaver Lake water. Experimental nutrient additions to Beaver Lake water were used to increase chl-a by three orders of magnitude. The formation potential of trichloromethane (TCM), which is a major component of TTHMs, increased by only 0.05 µg/L for every 1 µg/L increase in chl-a (Mash et al. 2014). Instead, the replication of the experiment across the growing season revealed a much larger potential for variation in TCM based on seasonal variations in DOC and other related chemical characteristics of the Beaver Lake source water. For example, TCM formation potential at 8 µg/L chl-a varied from less than 90 to more than 160 µg/L, across the different experiments over the growing season (Mash et al. 2014). However, the study did indicate that a greater amount of treatment resources would be necessary to disinfect and coagulate water with greater chl-a, which agrees with patterns observed since 2008 from the Beaver Water District.

The initial assessment criteria recommended here were based on the information and methods used to develop the chl-a and ST standards initially. However, in defining an assessment method, the regulatory agencies are effectively defining whether or not Beaver Lake is impaired for its designated beneficial uses, which include drinking water supply. As stated previously, choosing the recommended minimum allowable exceedances (3 out of 5 years, 4 out of 7 years, 5 out of 9 years, or 6 out of 11 years) will likely result in an immediate listing of

Beaver Lake. Although we maintain the primary recommendation that the minimum number of exceedances that trigger a water-quality violation should be greater than one-half the number of years in the assessment period, regulatory agencies may prefer to consider other assessment options which would not immediately result in listing Beaver Lake as impaired. We identify a few of those options in the following text.

Other Assessment Options

A number of other assessment options could be appropriate for the chl-a and ST criteria for Beaver Lake at Hickory Creek. Each of these considerations are first based on the fact that the standards were effectively equivalent to a long-term expected average condition in Beaver Lake at Hickory Creek. Thus, they first comply with our assessment methodology recommendation. They also offer possibilities for decreasing the risk of a violation based on how the growing season geometric mean chl-a and annual average ST data are assessed.

Consider a Long-Term Assessment Period – ADEQ currently relies primarily on a five year assessment period. As stated previously, the use of greater than 1 violation in a five year period suggests a 40% loss of use, which ADEQ often relies on in assessment (ADEQ personal communication, 2014). However, we have demonstrated in this study that a more than one in five year assessment is inappropriate because the adopted standards were equivalent to expected long-term average conditions. Indeed our analysis is supported by the fact that four of six growing season geometric mean chl-a and three of six annual average ST measured at the Hickory Creek location in Beaver Lake exceed the water quality standards. Expanding the assessment period to seven, nine, or even eleven years would allow one to five additional years of data to be collected to inform the current assessment. Multiple studies have indicated that

decadal-scale trends in chl-a in lakes may be related to climatic variability (Arhonditis et al. 2004, Hampton et al. 2008). A similar analysis has not yet been conducted for Beaver Lake, although that analysis is planned as part of the second and third phases of this project. In the meantime, using a longer assessment period that approaches or exceeds a decade in length (9 or 11 years) may capture the full range of potential chl-a variation due to climate variability.

The regulatory agencies could also consider using a rolling or moving average of the growing season geometric mean chl-a concentrations and the annual average ST. This would ‘smooth’ the variability in chl-a concentrations that could be driven by climatic patterns, lake management or anthropogenic factors. Although this approach was not explored in detail, the same analysis used in this study could be applied to the moving average over a defined period. However, the constraint that the criteria promulgated were effectively representative of the long-term average condition at Hickory Creek still influences the probabilities of exceedance – because even a moving average of the growing season geometric mean chl-a or annual average ST for the Hickory Creek location should be approximately equivalent to the numeric criteria defined for Beaver Lake. For example, there was a 32% risk that a five-year moving average of the annual average ST would be less than 1.1 m in two out of five years at Hickory Creek. The risk that the chl-a criteria would be exceeded in two out of five years was 86% when using a five year moving average of the growing season geometric mean chl-a concentrations at Hickory Creek.

Consider Coupling the Standards – The chl-a and ST were likely intended to be considered as separate. In other words, a violation of either standard would result in listing the lake as impaired. However, the patterns in chl-a and ST in Beaver Lake conform to common limnological models that have been used to manage eutrophication. Thus, the growing season

geometric mean chl-a concentration and annual average ST at Hickory Creek are strongly related because chl-a concentration largely controls ST (Carlson 1977). Thus, another option for decreasing the risk of listing Beaver Lake as impaired given the current promulgated standards would be to require that both standards are violated in more than half of the years in which the lake is assessed. This assessment method would provide the most conservative approach for listing the lake as impaired because it effectively decreases the risk of a single variable resulting in a water quality violation. Instead, the approach relies on confirmatory evidence and is supported by the fact that Beaver Lake conforms to common limnological models that show a strong relationship between chl-a and ST.

Consider Revising the Standards – As currently adopted into Arkansas State Law, the chl-a and ST standards apply to a growing season geometric mean and an annual average, respectively, observed in monthly sampling at the Hickory Creek location in Beaver Lake. The standard values were based on a weight of evidence approach, but the location to which they were applied in Beaver Lake was effectively equivalent to the expected long-term average conditions. Thus, another possible consideration for assessment is moving the location against which the criteria are evaluated. This would allow room for variation so that the minimum number of violation could be less than half of the years in an assessment period, because the long-term expected average conditions downstream of Hickory Creek were expected to be less than the promulgated standards. The probability of exceedance analysis presented within this study could be used to inform regulatory agencies and stakeholders on the number of exceedances allowed with an assessment period. For example, two or more exceedances for chl-a and/or ST in five years at Lowell would be within the desired risk (20% or less). When using a five year moving average, there was a 10% or less risk that two or more exceedances would occur in five years for chl-a or

ST. The difficulty with this approach is that the actual monitoring location is currently written into Arkansas Regulation No. 2, and would require a revision to the standard.

The options presented in this section were intended to demonstrate how water quality in Beaver Lake could be assessed against the promulgated standards that would minimize the risk of exceeding the standards. We have provided these considerations because in selecting an assessment methodology, the regulatory agencies are effectively tasked with identifying whether or not the lake is impaired based on current conditions. This choice is subjective and the considerations provided in this section represent scientifically-defensible approaches that could be used to identify a violation or non-violation based on current conditions. That choice is beyond the scope of the science and instead relies on the opinion of the regulatory agencies in concert with input from various stakeholders, which should be informed by science.

Limnological Patterns in Beaver Lake and Data Limitations

As expected according to reservoir limnology theory (Thornton et al. 1990), chl-a concentrations decreased and STs increased along the riverine-transition-lacustrine gradient in Beaver Lake. More importantly, chl-a concentrations among these sites varied predictably according to the model for natural lakes proposed by Dillon and Rigler (1974). Similarly, the ST in Beaver Lake was strongly related to chl-a concentrations and conformed to the model proposed by Carlson (1977). Thus, Beaver Lake is similar to many reservoirs in that its productivity is greatest near the inflow and diminishes closer to the dam. But, the lake also conforms to common limnological models that are often used in water-quality management decisions for natural lakes.

The probability analyses used to derive assessment methodologies in this project require relatively long-term data and assume no directional change over the period of record. It is important to note that both of these requirements had to be stretched in order to complete the analysis. For example, long-term data were not available for the Hickory Creek location, so a modeling approach based on the original standard development (FTN 2008) was used to calculate exceedance probabilities for this site. Further, there was a long-term trend in the growing season geometric mean chl-a and annual average ST at the Lowell location. No trends were apparent at the other monitoring locations. However, too few data were available to assess this trend at Hickory Creek.

The occurrence of long-term trends at the Lowell location at Beaver Lake support the idea that algal biomass is increasing through time at this location. What remains unknown is whether or not these trends were driven by changes in the watershed or by long-term climate-based variability (Arhonditis et al. 2004, Hampton et al. 2008). These possibilities will be explored in the next phase of the project. For the purposes of this project, we simply acknowledge this trend observed at a single monitoring location and developed the following recommendations based on the probability analyses shown in the results.

It is important to emphasize that long-term data were not available at the Hickory Creek location when the chl-a and ST standards were developed and adopted (FTN 2008). As a result, the standard developers used a regression relationship between measured values at the Highway 412 and Lowell locations for both chl-a and ST to derive estimates for these parameters at Hickory Creek. Their model had very poor predictive power for chl-a ($R^2 = 0.11$; $p = 0.1$), but was stronger for ST ($R^2 = 0.55$; $p < 0.001$). The poor predictive power of their model was perhaps attributable to limited data available for their analysis. That same analysis was repeated

for chl-a predictions at Hickory Creek in this study (predicted data in Table 2). Although the chl-a model was substantially improved using USGS data collected from 2001-2014 ($R^2 = 0.40$; $p = 0.03$), the predictions derived from the model were not strongly correlated to the measured values between 2009-2014 (Figure 7a). We also used a direct predictive model to estimate the ST at Hickory Creek from the ST at Lowell, which was stronger than the model developed by FTN (2008). The ST model using data from 2001-2008 performed better ($R^2 = 0.75$; $p = 0.01$), and predicted values were reasonably correlated with measured values between 2009 and 2014 (Figure 7b).

The reliance on predicted data at Hickory Creek for standard development is important, particularly given the poor prediction power of the models derived from existing data (Figure 7). Thus, the exceedance probabilities calculated using these data could be unreliable. However, the exceedance probability calculated for the Highway 412 location and Lowell locations were based on actual direct measurements. Because the exceedance probabilities at Hickory Creek fell between the exceedance probabilities at the Highway 412 location and Lowell (Figure 4), the estimates should be reasonably realistic. Nevertheless, the chl-a and ST standards for Hickory Creek should be re-evaluated when sufficient data (> 10 years) are available.

One issue that should be reiterated is the possible lack of stationarity in the data collected between 2001-2014. Although the Lowell location was the only one in which growing season geometric mean chl-a and annual average ST were changing through time, the relationships between these variables and time at the other locations may suggest a weak trend. Thus, a more detailed examination of the trends is necessary to understand if chl-a and ST are changing in Beaver Lake. If these parameters are changing, the next obvious question will be why? It is entirely possible that changes in the watershed could be leading to increased nutrient inputs that

are driving increased chl-a and decreased ST. However, it is also possible that the trends in these data are attributable to long-term climatic variation, which has been shown for other lakes around the world (Arhonditsis et al. 2004; Hampton et al. 2008). Thus, phases two and three of the current project, which will evaluate trends in the in-lake variables and watershed nutrient concentrations will provide crucial information as to if and how the lake may be changing with time and what effect watershed management could have on reversing these trends.

Conclusion

The purpose of this project was to derive an initial assessment methodology based on the original methods used to develop the chl-a and ST standards for Beaver Lake. Based on the methods for standard development, we have offered a specific recommendation that the minimum number of exceedances that trigger a water-quality violation should be greater than one-half the number of years in the assessment period. Adopting this minimum alone would likely result in a violation of the water quality standards for Beaver Lake, based on the current data available for Beaver Lake at Hickory Creek and the exceedance probabilities derived using the approach used to develop the standards. Thus, we have also offered several other considerations that would minimize the risk of listing the lake as impaired in an immediate assessment. We have offered these options because the values of the standards were not originally expected to result in immediate water quality violations in Beaver Lake (FTN 2008). Thus, these considerations provide the regulatory agencies with scientifically-defensible approaches to decide, based on current data, whether or not Beaver Lake is impaired for its designated beneficial uses.

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Table 1. Chlorophyll a (chl-a) water quality standards along with respective assessment methods for various states (adapted from EPA 2014 web site).

State	Criteria Status	chl-A Criteria ($\mu\text{g L}^{-1}$)	Assessment Methodology	Type
Alabama	Partial	5-27	Mean of the photic-zone based on composite water samples collected monthly April through October shall not exceed criteria, as measured at the deepest point in the water body	site specific 37 water bodies
Arkansas	Partial	8	TBD	site specific
Georgia	Partial	5-27	Mean of monthly photic zone composite samples shall not exceed value from April through October	site specific 19 water bodies
Missouri*	Partial	1.5-11 [general rule Chl-a:TP ratio 0.42-0.44]	Geometric mean of a minimum of 4 samples per year that are not necessarily consecutive and must be collected from the surface and near the outflow from May through August	site specific 28 sites
Nebraska	Partial	8-10	Seasonal mean from April through September	site specific eastern western
Oklahoma	Partial	10	Long-term mean at a depth of 0.5 meters below the surface	site specific water supply
Tennessee	Partial	18	Mean of the photic-zone composite samples collected monthly from April to September shall not exceed criteria as measured over the deepest point, main river channel, or dam fore bay	site specific Pickwick Reservoir
Texas	Partial	5-20	Based on the long-term median of water samples from individual reservoirs	site specific 39 sites

Table 2. Growing season geometric mean chlorophyll (chl-a) concentrations for each sampling location on Beaver Lake. Samples were collected at Hickory Creek since 2009, but a regression model was used to estimate values for the period of record.

Year	Sampling Site (distance from inflow [km])					
	HWY 412 (0.0)	Hickory Creek (8.9)	Hickory Creek* (8.9)	Lowell (12.2)	HWY 12 (21.5)	Dam (45.9)
	Growing Season Geometric Mean Chl-a (µg/L)					
2001	12.8		9.6	6.1	2.9	0.5
2002	6.1		5.2	4.6	4.5	2.0
2003	13.6		10.1	4.9	3.2	0.9
2004	3.0		3.1	1.4	4.1	1.4
2005	11.0		8.4	3.7	2.7	1.3
2006	8.2		6.6	4.2	3.0	1.6
2007	9.5		7.4	5.9	2.9	1.1
2008	13.7		10.2	7.9	5.5	3.1
2009	16.3	9.6	11.9	9.5	5.6	1.5
2010	6.9	12.3	5.8	8.3	3.9	1.9
2011	12.9	7.0	9.7	5.7	5.0	2.1
2012	18.8	11.2	13.6	8.8	3.8	1.1
2013	10.4	9.3	8.0	7.3	4.9	1.8
2014	16.2	8.0	11.8	5.8	2.4	1.0
Average	11.4	9.6	8.7	6.0	3.9	1.5

*Data predicted from regression relationship derived from samples at HWY 412 and Lowell.

Table 3. Annual average Secchi transparency (ST) for each sampling location on Beaver Lake. Samples were collected at Hickory Creek since 2009, but a regression model was used to estimate values for the period of record.

Year	Sampling Site (distance from inflow [km])				
	HWY 412 (0.0)	Hickory Creek (8.9)	Hickory Creek* (8.9)	Lowell (12.2)	HWY 12 (21.5)
	Annual Average ST (m)				
2001	0.9		1.5	2.1	2.8
2002	1.1		1.2	1.5	2.0
2003	0.9		1.4	1.9	2.4
2004	1.2		1.2	1.6	1.7
2005	1.0		1.3	1.7	2.0
2006	1.0		1.3	1.7	2.2
2007	1.1		1.3	1.8	1.7
2008	0.8		1.0	1.1	1.7
2009	0.9	1.0	1.1	1.2	1.7
2010	0.4	1.1	1.1	1.4	2.1
2011	1.0	1.0	0.9	1.0	1.4
2012	0.7	1.0	1.0	1.1	1.9
2013	0.9	1.2	1.2	1.4	2.2
2014	0.8	1.2	1.2	1.6	2.1
Average	0.9	1.1	1.2	1.5	2.0

*Data predicted from regression relationship derived from samples at Lowell and Hickory Creek.

Table 4. The number of years that the chlorophyll a (chl-a) and Secchi transparency (ST) standards are expected to violated at the Hickory Creek location in Beaver Lake using a 10% or 20% allowable risk across a 5- to 11-year assessment period with data collected from 2001 – 2008 or 2001 – 2014.

	# of Years that Standard Exceeded at Hickory Creek Based on 10% Risk	# of Years that Standard Exceeded at Hickory Creek Based on 20% Risk
2001-2008 Data Chl-a Data		
5 Year Assessment	3	3
7 Year Assessment	4	3
9 Years	5	4
11 Years	6	5
2001-2014 Chl-a Data		
5 Years	5	4
7 Years	6	5
9 Years	8	7
11 Years	9	9
2001-2008 ST Data		
5 Years	2	1
7 Years	2	2
9 Years	3	2
11 Years	4	3
2001-2014 ST Data		
5 Years	3	2
7 Years	4	3
9 Years	5	4
11 Years	6	5

Figure 1. Beaver Lake in Northwest Arkansas including the locations of the five routine monitoring stations from which recent long-term data were available.

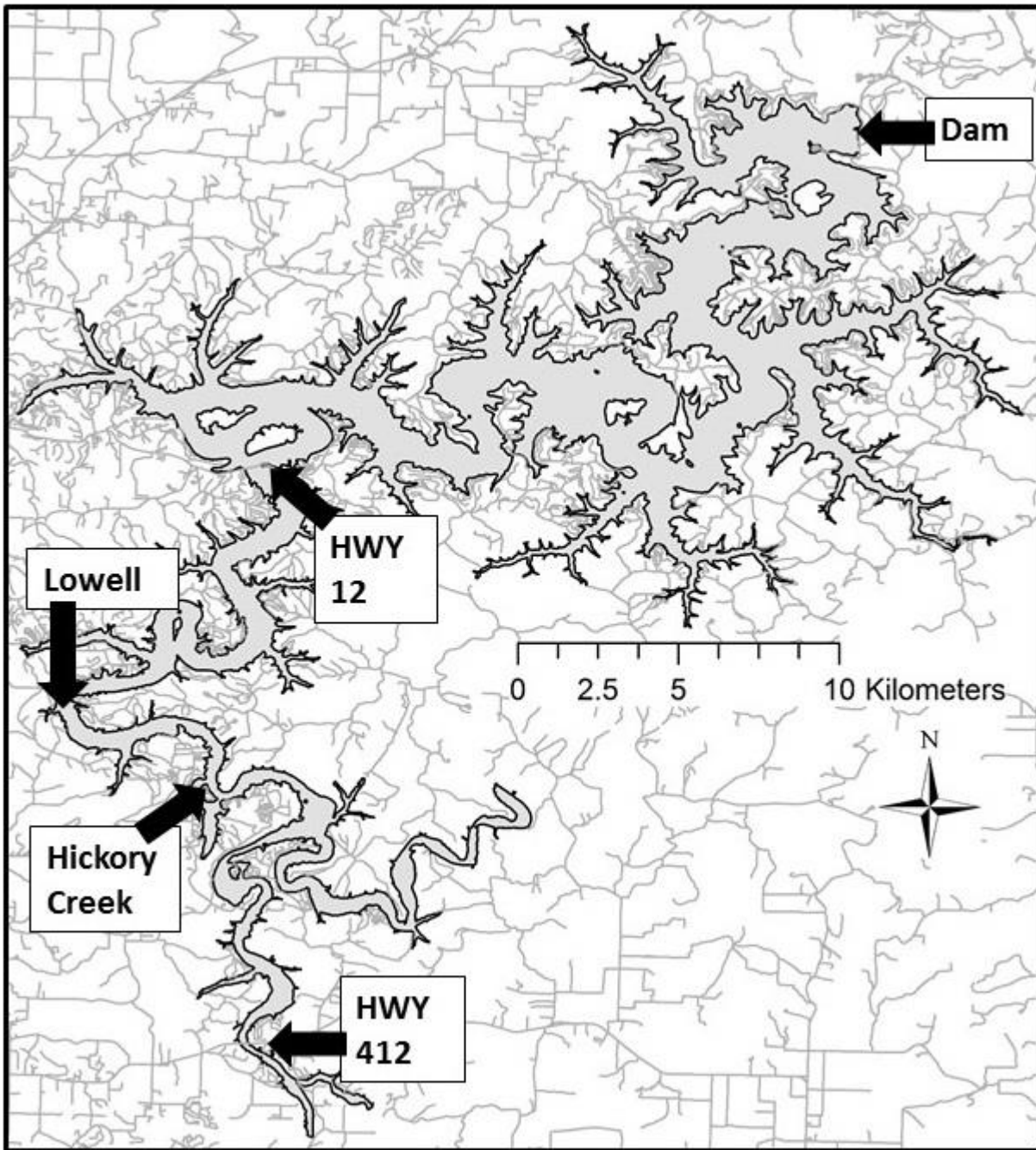


Figure 2. A) Relationship between average summer total P concentration and average summer chlorophyll a (chl-a) concentration in lakes from Dillon and Rigler (1974) along with data from each location on Beaver Lake, B) Relationship between average summer chl-a concentration and average summer Secchi transparency (ST) from Carlson (1977) along with data from each location on Beaver Lake.

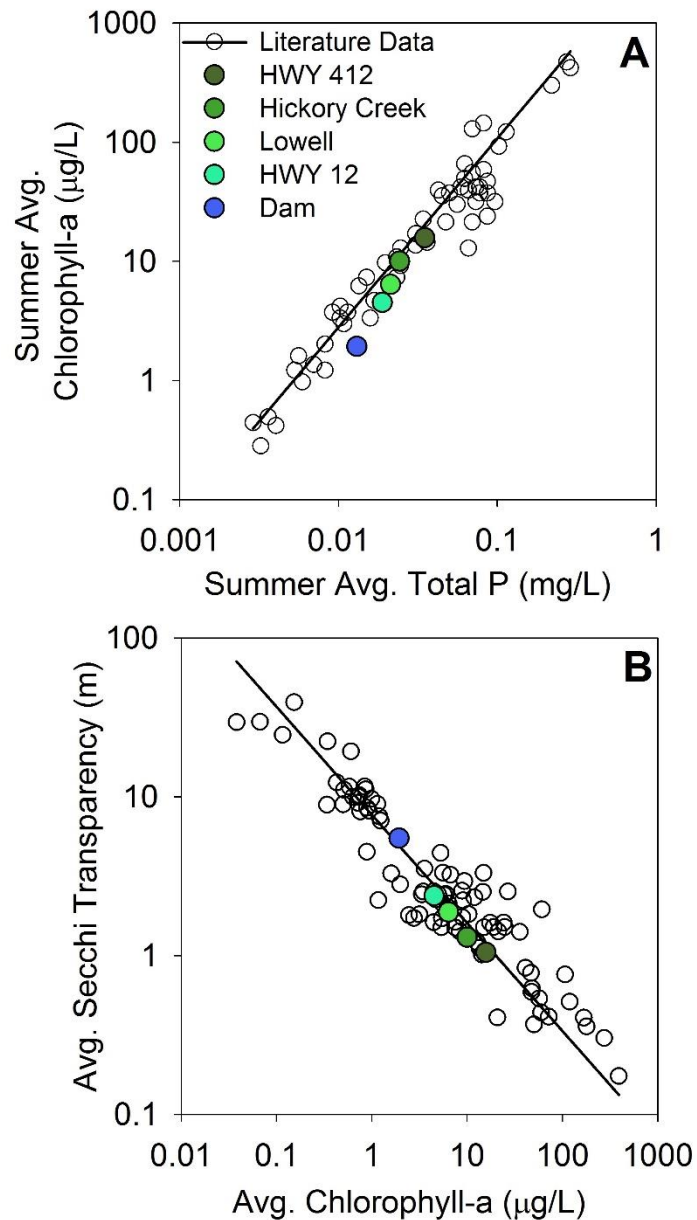


Figure 3. Long-term trends in A) growing season geometric mean chlorophyll a (chl-a) concentrations, and B) annual average Secchi transparencies (ST) at sites in Beaver Lake.

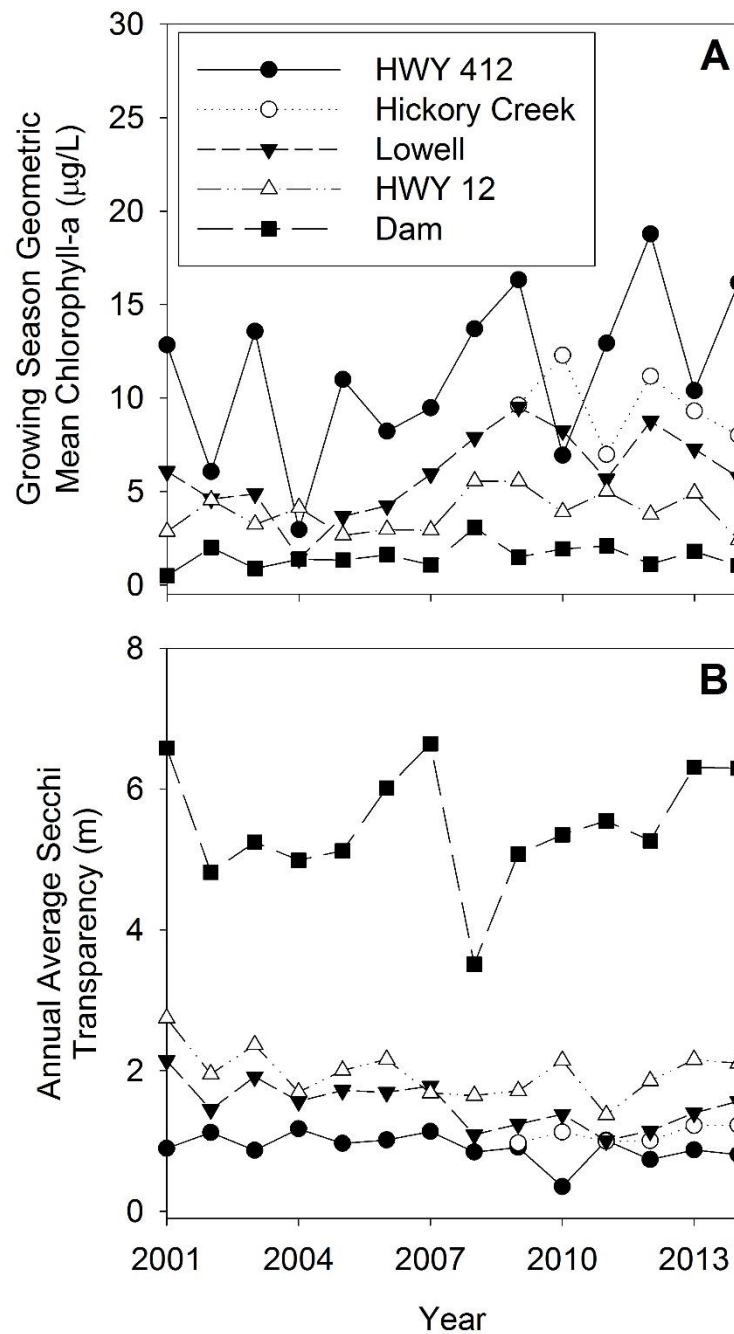


Figure 4. Probability of exceeding the water quality standards for A) chlorophyll a (chl-a) and C) Secchi transparency (ST) using data collected before 2009 and data from the entire period of record; and the mean of observed values from 2009-2014 for B) chl-a and D) ST along the riverine-transition-lacustrine gradient in Beaver Lake.

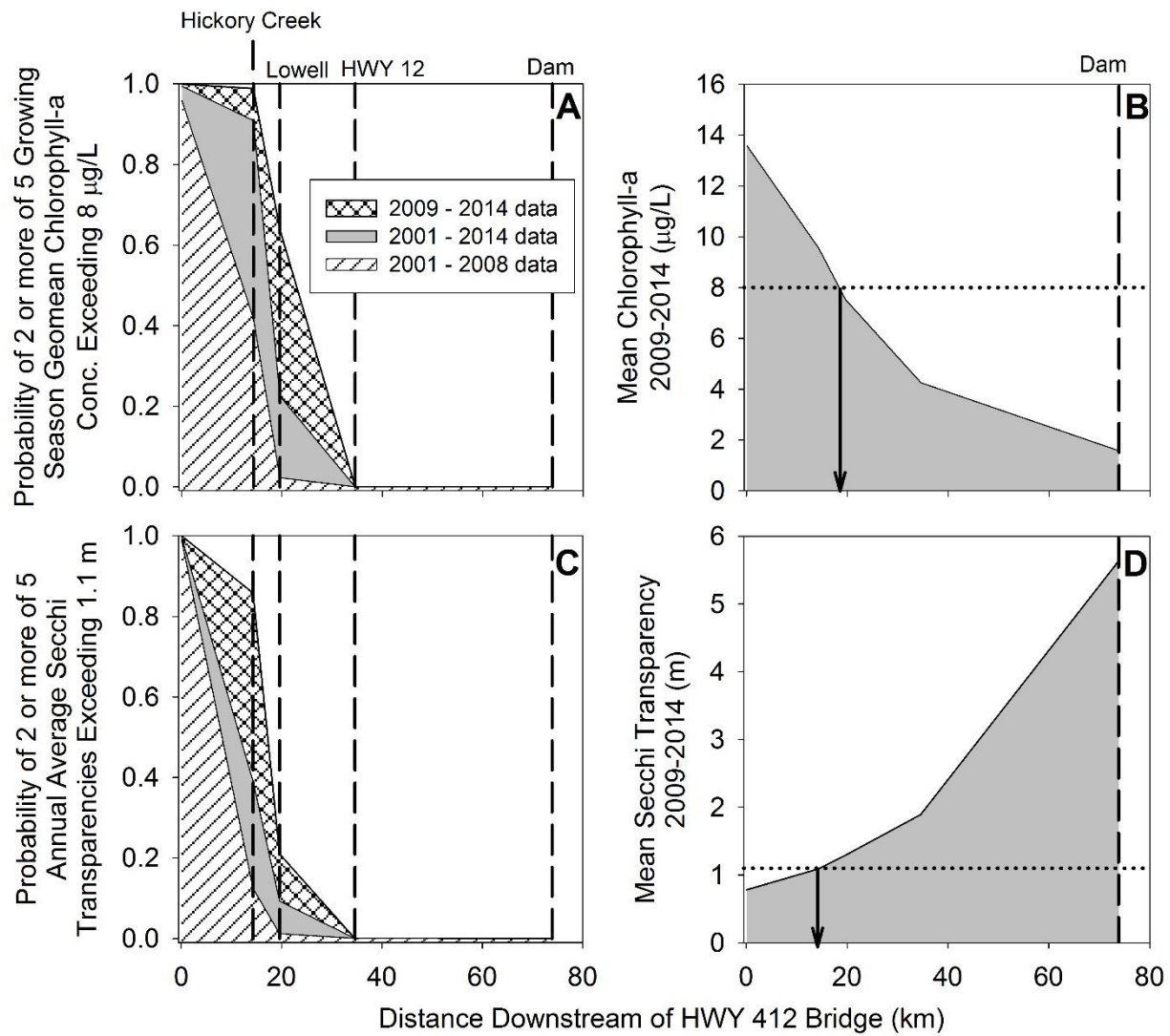


Figure 5. Probability of exceeding the 8 $\mu\text{g/L}$ growing season geometric mean chlorophyll a (chl-a) standard where the number of exceedances is varied across a variable assessment period for A) Highway 412 using 2001-2008 data, B) Highway 412 using 2001-2014 data, C) Highway 412 using 2009-2014 data, D) Hickory Creek using 2001-2008 data, E) Hickory Creek using 2001-2014 data, F) Hickory Creek using 2009-2014 data, G) Lowell using 2001-2008 data, H) Lowell using 2001-2014 data, I) Lowell using 2009-2014 data, J) Highway 12 using 2001-2008 data, K) Highway 12 using 2001-2014 data, L) Highway 412 using 2009-2014 data.

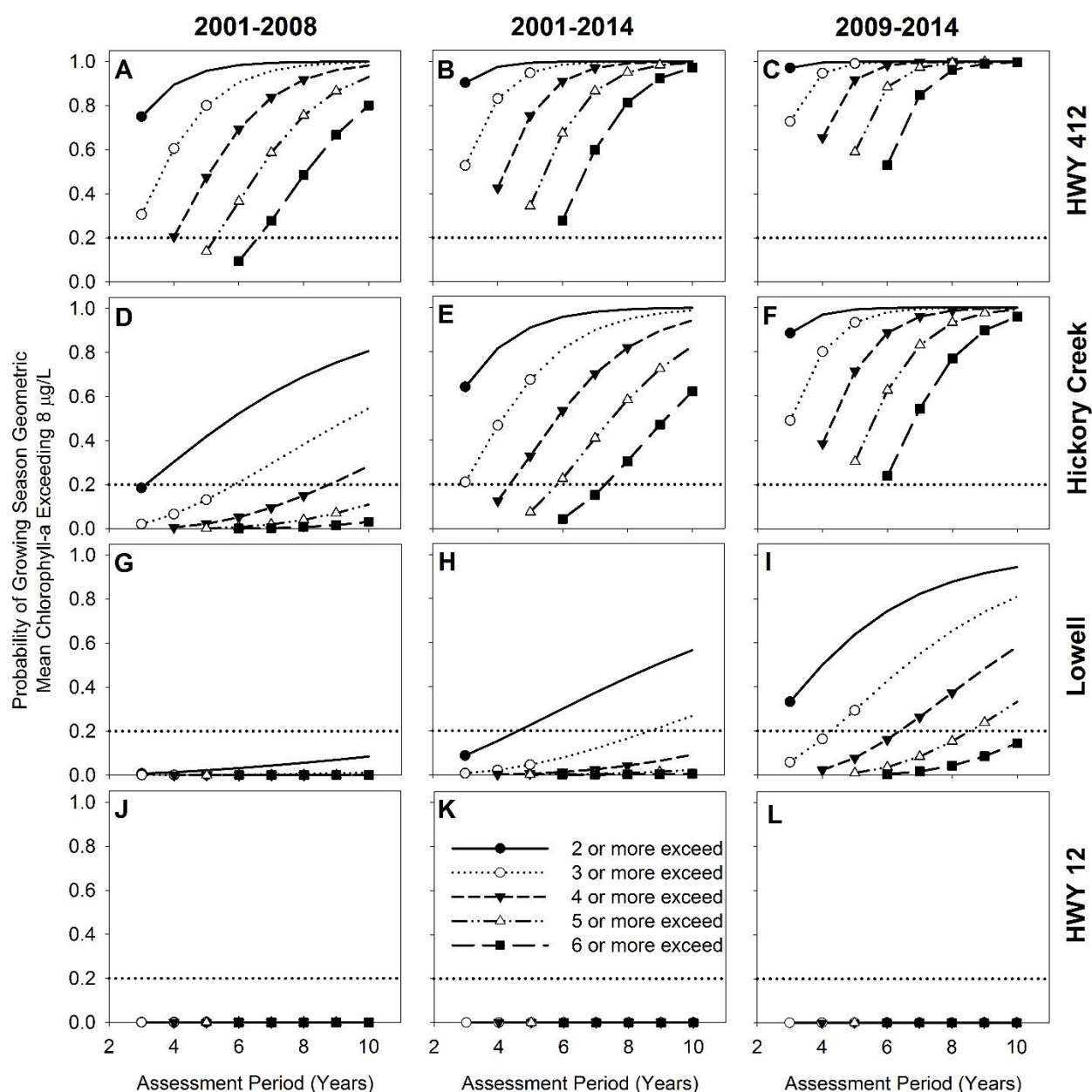


Figure 6. Probability of exceeding the 1.1 m average annual Secchi transparency (ST) standard where the number of exceedences is varied across a variable assessment period for A) Highway 412 using 2001-2008 data, B) Highway 412 using 2001-2014 data, C) Highway 412 using 2009-2014 data, D) Hickory Creek using 2001-2008 data, E) Hickory Creek using 2001-2014 data, F) Hickory Creek using 2009-2014 data, G) Lowell using 2001-2008 data, H) Lowell using 2001-2014 data, I) Lowell using 2009-2014 data, J) Highway 12 using 2001-2008 data, K) Highway 12 using 2001-2014 data, L) Highway 412 using 2009-2014 data.

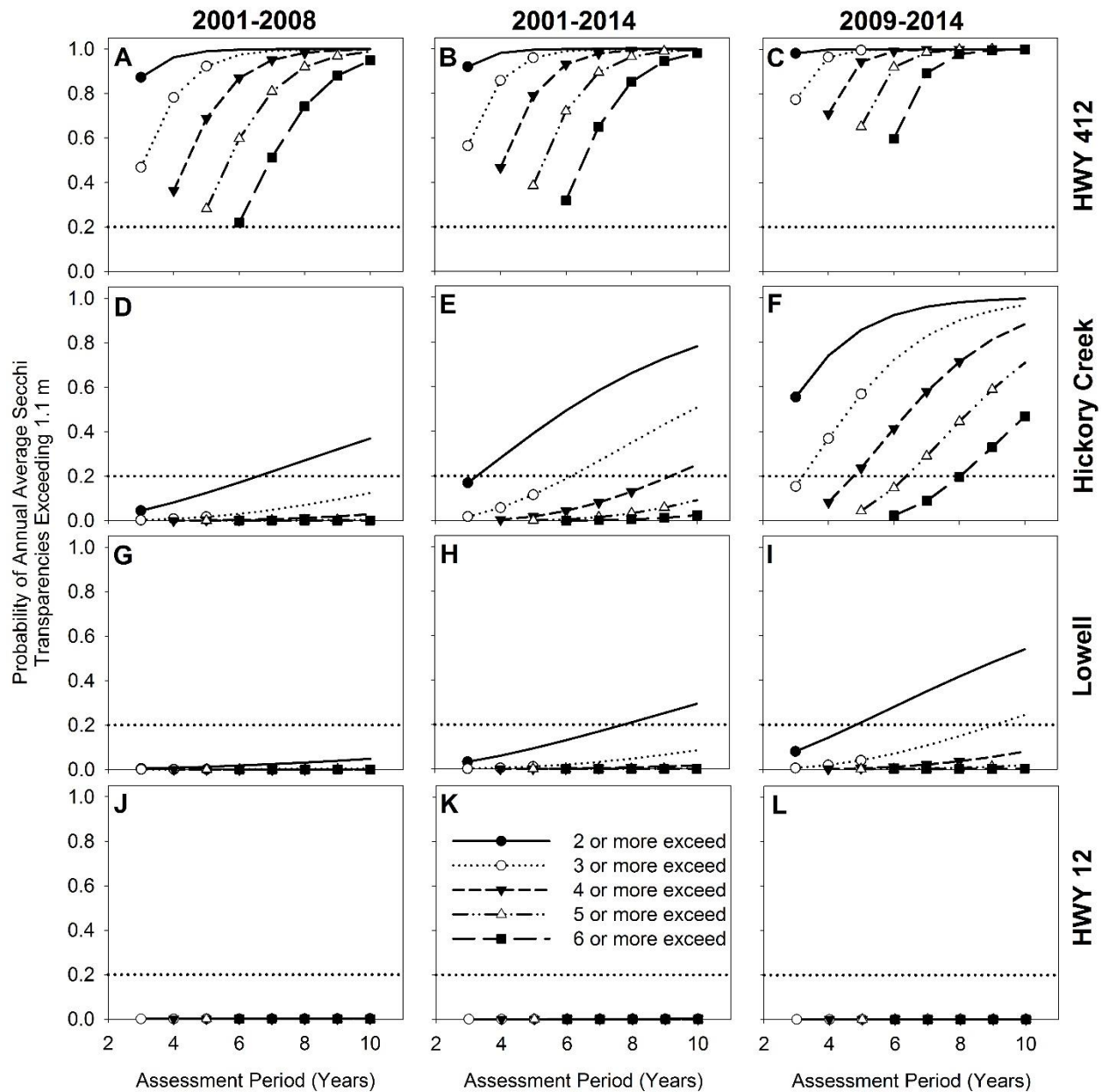


Figure 7. Predicted and measured values for A) growing season geometric mean chlorophyll a (chl-a) concentrations and B) annual average Secchi transparency (ST) at Beaver Lake at Hickory Creek for 2009-2014.

