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Implementing Effects-Based Water Quality Criteria for Eutrophication in Beaver Lake, Arkansas: Linking Standard Development and Assessment Methodology

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Abstract

To address water quality standards needed to prevent accelerated eutrophication, many states in the United States have developed effects-based standards related to nutrients. In many cases, this has resulted in specific standards for Secchi transparency (ST) and phytoplankton biomass measured as sestonic chlorophyll *a* (chl-*a*). The state of Arkansas recently adopted its first effects-based water quality criteria for Beaver Lake in northwestern Arkansas, which was a growing-season geometric mean chl-*a* <8 μg L^{-1} and an annual average ST >1.1 m. However, the adopted standard did not have a predefined assessment methodology that outlined the frequency and duration of potential exceedances. This study used hydrologic frequency analysis to estimate the risk of exceeding these water quality standards using measured and modeled data from Beaver Lake from 2001 to 2014. Beaver Lake conformed to common models in reservoir limnology in that ST was least and chl-*a* was greatest in the river–reservoir transition zone and decreased in the downstream direction toward the dam. Greater chl-*a* and lesser ST was clearly related to total phosphorus concentrations along this gradient. Thus, the risk of exceeding the water quality criteria decreased in a downstream direction. There were substantial differences in the probability of exceeding the adopted water quality criteria based on both spatial and temporal variation in the potential assessment periods. Based on the way the standard was developed and the risk of exceeding these standards derived from data collected before the standards were in place, we recommend that a minimum of half of the years assessed be necessary to result in a water quality violation. A number of other assessment considerations are presented that could provide flexibility to regulatory agencies in assessing water quality standards.

Core Ideas

- Linking water quality assessment methods to standard development has not been well established for numeric nutrient criteria.
- Effects-based criteria are becoming more common but with little consideration of intra- and interannual variability and their influence on assessment.
- Failure to consider assessment options in advance could result in unintended consequences during water quality assessment.

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The USEPA has called on states to develop nutrient criteria or numeric translators for narrative criteria that would be protective of beneficial uses for all water bodies. The USEPA (2010a) recommended a weight-of-evidence approach to develop numeric nutrient criteria based on reference conditions, mechanistic modeling, or stressor–response analysis. State adoption of numeric nutrient criteria has 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 connection back to nutrient concentrations in effects-based criteria comes from well-developed models that provide a quantitative link between total phosphorus (P) and chl-*a* (Dillon and Rigler, 1974) or Secchi transparency (ST; Carlson, 1977). Thus, water quality improvements in chl-*a* or ST are linked to the quantitative reductions necessary for total P (Cooke et al., 2005), which can be implemented through watershed management (Jarvie et al., 2013; Sharpley et al., 2014).

Twenty-two states have adopted chl-*a* water quality criteria on a statewide basis, for specific groups of waterbodies, or on a lake-specific basis (Table 1; USEPA, 2014). These water quality standards were developed by the states and approved by the USEPA in accordance with the Clean Water Act (40 CFR 131), which requires that the standards protect a beneficial use of water (Haggard and Scott, 2010). Designated uses help define water quality objectives, which can be used in combination with environmental data, models, and expert judgment to define a specific numeric threshold that would identify a water quality violation. This differs from the development of an assessment methodology, which typically occurs after a water quality standard is adopted by states and approved by the USEPA. The assessment method defines the period of time during which a water quality assessment will occur and also defines the number of allowable violations of a water quality standard within the assessment period.

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, a man-made impoundment of the White River, in northwestern Arkansas. According to the state's Regulation no. 2, which is the state

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Abbreviations: chl-*a*, chlorophyll *a*; ST, Secchi transparency.

regulation defining water quality standards (Arkansas Pollution Control and Ecology Commission, 2012), the growing season (May–October) geometric mean chl-*a* concentration in Beaver Lake near Hickory Creek shall not exceed 8 μg L^{-1} and the annual average ST shall not be <1.1 m. The Hickory Creek location was chosen because it is upstream from all municipal water intakes. However, the site is also in the riverine-transition zone of Beaver Lake, which like most reservoirs is known to have greater primary production and phytoplankton biomass than the downstream lacustrine zone (Kimmel et al., 1990; Lind et al., 1993; Scott et al., 2009).

The chl-*a* and ST standards were adopted from the recommendations of a working group that conducted an analysis using data from Beaver Lake and other reservoirs in the region (FTN Associates, 2008). The basis for choosing the 8 μg L^{-1} chl-*a* standard and the 1.1-m ST standard came from a weight-of-evidence approach that included chl-*a* and ST standards in neighboring states, ecoregional chl-*a* and ST values, percentile distributions for Beaver Lake data, empirical information on nutrient loading, and water quality modeling (FTN Associates, 2008). Although not explicitly stated in the document, the recommended standards were approximately equivalent to the long-term expected average conditions at the Hickory Creek location in Beaver Lake (see supplemental material). Further, according to the perspective of the working group, water quality monitoring data collected immediately after 2008 were not expected to result in a water quality violation based on the proposed standard (FTN Associates, 2008).

The standard development process for chl-*a* and ST standards on Beaver Lake did not include any recommendations for an assessment methodology that defined the period of time during which a water quality assessment would occur and the number of allowable violations of the water quality standard within the assessment period. Linking observed water quality measurements to numerical or statistical distributions is necessary for identifying water quality impairment (Zeng and Rasmussen, 2005). A common assessment methodology used in surface water assessment by the state of Arkansas is to allow no more than one violation in a 5-yr assessment period (Arkansas Department of Environmental Quality, personal communication, 2014). However, the adopted standards were equivalent to a long-term expected average condition in Beaver Lake at Hickory Creek. Thus, assuming that 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 that the state assessment methodology be consistent with the information used to develop the water quality standards for Beaver Lake.

The chl-*a* and ST numeric criteria for Beaver Lake provide a useful example of how the uncoupled development of water quality standards and the associated assessment methodology could lead to unintended or potentially unnecessary water quality violations. The objective of this study was to hindcast the compliance of Beaver Lake water quality with the state-mandated water quality standards for chl-*a* and ST. In particular, we were interested in demonstrating how spatial and temporal variation in these variables could influence the compliance outcomes given a variety of assessment options. Temporal variation was tested by comparing data among years and exploring temporal trends in chl-*a* and ST from 2001 to 2014. Spatial variation was tested by comparing data among sites along the riverine–transition–lacustrine gradient consistent with reservoir limnology theory (Thornton et al., 1990). Results of these hindcasts were used to develop assessment methodology options that could be implemented by the state.

Methods

Study Site and Data Description

Beaver Lake is a large multi-use reservoir of the US Army Corps of Engineers on the White River in Arkansas, and it is the most upstream reservoir on the river system; the downstream US Army Corp of Engineers 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 (US Army Corp of Engineers, 1998), and the reservoir is also used for recre-

Table 1. Chlorophyll *a* (chl-*a*) water quality standards along with the respective assessment methods for various states (adapted from USEPA, 2014).

State	Criteria status	Chl-*a* criteria	Standard application	Type
		μg L^{-1}		
Alabama	partial	5–27	mean of the photic zone based on composite water samples collected monthly April–October shall not exceed criteria, as measured at the deepest point in the water body	site specific, 37 water bodies
Arkansas	partial	8	to be determined	site specific
Georgia	partial	5–27	mean of monthly photic-zone composite samples shall not exceed value from April–October	site specific, 19 water bodies
Missouri	partial	1.5–11†	geometric mean of a minimum of four samples per year that are not necessarily consecutive and must be collected from the surface and near the outflow from May–August	site specific, 28 sites
Nebraska	partial	8–10	seasonal mean April–September	site specific, eastern or western
Oklahoma	partial	10	Long-term mean at a depth of 0.5 m below the surface	site specific, water supply
Tennessee	partial	18	mean of the photic-zone composite samples collected monthly April–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

† General rule: chl-*a*/total P ratio 0.42–0.44.

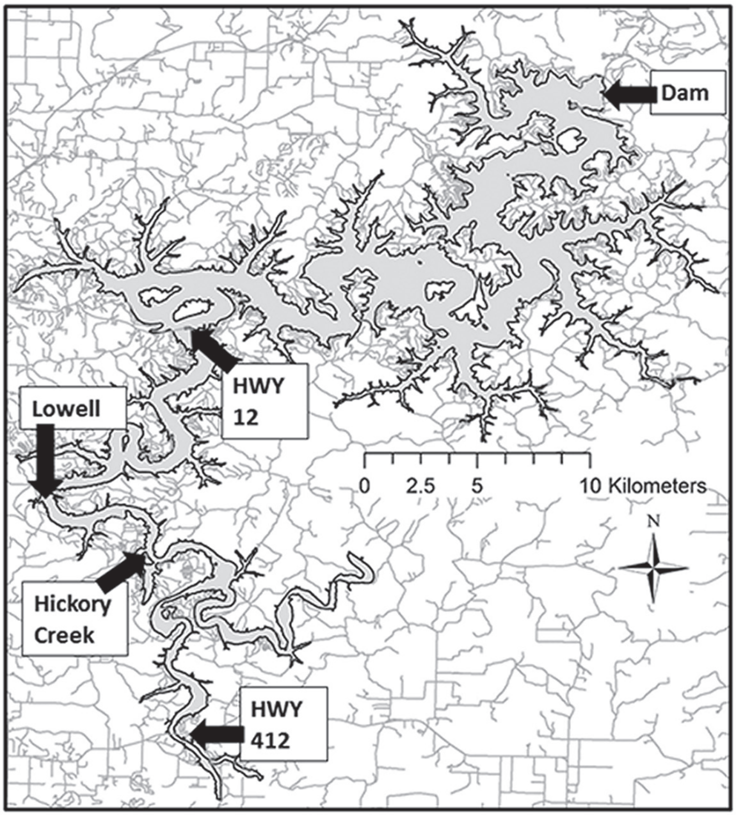

Fig. 1. Beaver Lake in northwestern Arkansas, including the locations of the five routine monitoring stations from which recent long-term data were available.

ation and fish and wildlife management. Beaver Lake is the water supply for northwestern Arkansas, providing domestic water to approximately 400,000 citizens and multiple industries. There are currently four public water suppliers using the reservoir, and the most upstream is the Beaver Water District. 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 Associates, 2008).

The USGS measures ST and collects water samples routinely from Beaver Lake at five locations (Fig. 1). Water samples were collected at approximately 2 m below the surface, transported to the USGS National Water Quality Laboratory, and analyzed for chl-*a* and other typical water quality constituents. Sampling occurred approximately six to eight times per year on average, and the frequency of collection was greater during the growing season (defined as May–October). Like most USGS monitoring data, the Beaver Lake data were uploaded into the National Water Information System (NWIS) that is managed and maintained by the USGS.

Data from the USGS NWIS database were 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. A growing season (May–October) geometric mean chl-*a* concentration was computed for each site in all CYs, and the annual arithmetic average ST was also computed. The water quality standard is currently assessed using data from Hickory Creek, as defined by Arkansas Regulation no. 2 (Arkansas Pollution Control and Ecology Commission, 2012). However, water sampling at Hickory Creek (by the USGS) began only in CY 2009. Thus, data were 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 NWIS (http://waterdata.usgs.gov/nwis).

Predicted Data

Because data at Hickory Creek were only available for CYs 2009 through 2014, this would provide only six geometric mean chl-*a* and arithmetic average ST values from which to estimate the probabilities of exceeding the defined criteria. Therefore, chl-*a* and ST at Hickory Creek were predicted based on available data at the other sites, consistent with the methods used in the standard development process (FTN Associates, 2008). By predicting values at Hickory Creek, we created a database with 14 yr 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.

To derive the expected values for Hickory Creek, we used a method similar to that in the standard development process (FTN Associates, 2008) in which the relationship between geometric mean chl-*a* concentration at Highway 412 and Lowell was used to predict chl-*a* at Hickory Creek. Briefly, a simple linear regression was used to develop a predictive equation between the geometric mean concentration of chl-*a* at Highway 412 and Lowell ($\text{chl-}a_{\text{Lowell}} = 0.3174\ \text{chl-}a_{412} + 2.385$, $R^2 = 0.40$, $p = 0.02$). This equation was used to predict the values at Lowell based on the observed geometric mean chl-*a* at Highway 412. The predicted geometric mean chl-*a* concentrations for Lowell were averaged with the measured geometric means at Highway 412 to estimate the values for Hickory Creek. 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 the expected ST data for Hickory Creek followed the same method. Briefly, we utilized measured data from 2009 to 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, there was a strong relationship between the annual average ST at Lowell and the annual average ST at Hickory Creek ($\text{ST}_{\text{Hickory}} = 0.5020\ \text{ST}_{\text{Lowell}} + 0.4436$, $R^2 = 0.75$, $p = 0.03$). This prediction model was then used to estimate the annual average ST for years in which measured ST values were not available for Hickory Creek.

Probability of Exceeding Criteria

The hydrologic frequency method was used to hindcast the probability that the growing season geometric mean chl-*a* was >8 μg L^{-1} and the annual average ST was <1.1 m. It is important to note that we use the term *exceedance* to indicate a growing season geometric mean that was >8 μg L^{-1} or annual average ST that was <1.1 m. In calculating exceedance probabilities, one major assumption was that the occurrence of each event or measurement against the criteria was a random stochastic process. The probability of a particular criterion being exceeded in any year was P_T, and this probability was independent and specifically not dependent on previous measurement against the criteria or the history of chl-*a* and ST in Beaver Lake. We calculated the probability of K occurrences or measurements exceeding the criteria in N years following

$$f\left(K;P_T,N\right)=\frac{N!}{\left(N-K\right)!K!}P_T^K\left(1-P_T\right)^{N-K} \qquad [1]$$

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 calculated the probability of the criteria being exceeded exactly two times ($K = 2$) in a 5-yr period ($N = 5$). This equation was used to calculate the entire spectrum of K occurrences during N years, such that in a 5-yr period, the probabilities of exactly zero, one, two, three, four, and five exceedances were estimated. The probabilities of two, three, four, and five exceedances were then summed to represent the probability of two or more measurements exceeding the criteria.

Equation [1] 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., geometric mean chl-*a* concentrations and annual average STs) from the USGS, and we used the reduced equation representing many types of hydrologic frequency analysis (from Haan et al., 1994):

$$X_T=\overline{X}\left(1+C_{\mathrm{V}}K_T\right) \qquad [2]$$

where X_T is the criterion of interest, $\overline{X}$ 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, and K_T 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 Z scores from the standardized cumulative normal distribution. Because X_T, C_{V}, and $\overline{X}$ are known variables, the equation was solved for K_T, which was then used to look up the corresponding Z score (Haan et al., 1994, Appendix 2) and estimate the probability of the criteria being exceeded in any given year, i.e., P_T.

We provided a probability analysis of exceeding the criteria for three time periods, including (i) 2001 through 2008, representing the time period used to develop the criteria and produce the original water quality standard development report (FTN Associates, 2008), (ii) 2001 through 2014, representing recent, continuous data available through the present day, and (iii) data collected from 2009 to 2014 for which measured data were actually available at the Hickory Creek location. Long-term data sets are preferable in hydrologic frequency analysis, assuming that the distribution of the values is stationary with time or without a long-term trend.

Results

Growing season geometric mean chl-*a* concentrations ranged from 0.9 µg L^{-1} in 2003 at the dam location to 18.8 µg L^{-1} 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 µg L^{-1} for each kilometer downstream from the Highway 412 location. Measured geometric mean chl-*a* concentrations at the Hickory Creek location ranged from 7.0 to 12.3 µg L^{-1} and were similar in range to the predicted values for the same period of time (5.8–13.6 µg L^{-1}), which were derived from the regression modeling technique.

Table 2. Growing-season geometric mean chlorophyll (chl-*a*) concentrations for five sampling locations on Beaver Lake: Hwy. 12 (0 km from inflow), Hickory Creek (8.9 km from inflow), Lowell (12.2 km from inflow), Hwy. 12 (21.5 km from inflow), and the dam (45.9 km from inflow). Samples were collected at Hickory Creek since 2009, but a regression model was used to estimate values for the period of record.

Year	Growing-season geometric mean chl-*a*					
	Hwy. 412	Hickory Creek	Hickory Creek†	Lowell	Hwy. 12	Dam
	µg L^{-1}					
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
Avg.	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.

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, the 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 kilometer downstream from the Highway 412 location. The 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 during the same period of time (0.9–1.2 m).

Growing season geometric mean chl-*a* concentrations were increasing by 0.29 µg L^{-1} yr^{-1} at Lowell ($R^2 = 0.30$, $p = 0.0440$) from 2001 to 2014 (Fig. 2a). Average annual ST was decreasing by 0.05 m yr^{-1} at Lowell ($R^2 = 0.41$, $p = 0.0143$) from 2001 to 2014 (Fig. 2b). There were 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 were insufficient

Table 3. Annual average Secchi transparency for five sampling locations on Beaver Lake: Hwy. 12 (0 km from inflow), Hickory Creek (8.9 km from inflow), Lowell (12.2 km from inflow), Hwy. 12 (21.5 km from inflow), and the dam (45.9 km from inflow). Samples were collected at Hickory Creek since 2009, but a regression model was used to estimate values for the period of record.

Year	Annual avg. Secchi transparency					
	Hwy. 412	Hickory Creek	Hickory Creek†	Lowell	Hwy. 12	Dam
	m					
2001	0.9		1.5	2.1	2.8	6.6
2002	1.1		1.2	1.5	2.0	4.8
2003	0.9		1.4	1.9	2.4	5.2
2004	1.2		1.2	1.6	1.7	5.0
2005	1.0		1.3	1.7	2.0	5.1
2006	1.0		1.3	1.7	2.2	6.0
2007	1.1		1.3	1.8	1.7	6.6
2008	0.8		1.0	1.1	1.7	3.5
2009	0.9	1.0	1.1	1.2	1.7	5.1
2010	0.4	1.1	1.1	1.4	2.1	5.4
2011	1.0	1.0	0.9	1.0	1.4	5.6
2012	0.7	1.0	1.0	1.1	1.9	5.3
2013	0.9	1.2	1.2	1.4	2.2	6.3
2014	0.8	1.2	1.2	1.6	2.1	6.3
Avg.	0.9	1.1	1.2	1.5	2.0	5.5

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

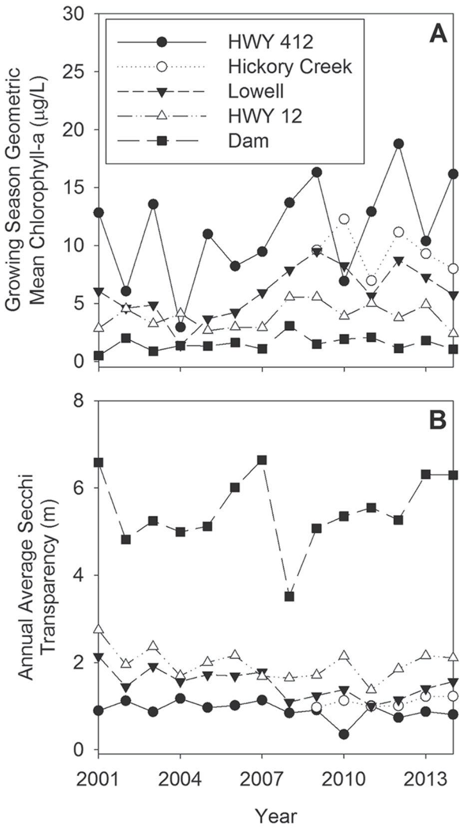

Fig. 2. Long-term trends in (A) growing-season geometric mean chlorophyll a concentrations, and (B) annual average Secchi transparencies at sites in Beaver Lake.

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 µg L^{-1} or the annual average ST exceeding 1.1 m in two or more years of a 5-yr assessment period differed across sampling locations and among the different data sets (2001–2008 vs. 2001–2014 vs. 2009–2014) used for the analysis (Fig. 3). There was a near-100% probability that the growing season geometric mean chl-*a* concentration would exceed 8 µg L^{-1} in two or more years of a 5-yr assessment period at the Highway 412 location, regardless of which data set was used (Fig. 3a). This probability dropped to approximately 40% at the Hickory Creek location when using data collected between 2001 and 2008. However, there was >90% probability that two or more growing season geometric mean chl-*a* concentrations would exceed 8 µg L^{-1} at Hickory Creek in the 5-yr assessment period when using data from 2001 to 2014 or 2009 to 2014 (Fig. 3a). For the Lowell location, these probabilities dropped to <5, 20, and 70% for the 2001 to 2008, 2001 to 2014, and 2009 to 2014 data sets, respectively. There was <1% probability that the growing season geometric mean chl-*a* concentration would exceed 8 µg L^{-1} two or more times in a 5-yr 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 to 2014 decreased from upstream to downstream, and the 8 µg L^{-1} target occurred approximately 20 km downstream from Highway 412, which corresponds closely with the Lowell sampling location (Fig. 3b).

There was a near-100% probability that the annual average ST would exceed 1.1 m in two or more years of a 5-yr assessment period at the Highway 412 location regardless of which data set was used (Fig. 3c). This probability dropped to approximately 10, 40, or 90% at the Hickory Creek location when using data collected between 2001 and 2008, 2001 and 2014, or 2009 and 2014, respectively. The probability of exceeding the annual average ST criteria at Lowell was 20% or less for all data sets (Fig. 3c). There was <1% chance that the annual average ST would exceed 1.1 m two or more times in a 5-yr 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 values from 2009 to 2014 increased from upstream to downstream, and the 1.1-m target occurred approximately 15 km downstream from Highway 412, which corresponds closely with the Hickory Creek sampling location (Fig. 3d).

In general, as the assessment period was increased from the 3 to 10 yr, the probability of observing values greater than the 8 µg L^{-1} growing season geometric mean (Fig. 4) or less than the 1.1-m annual average ST (Fig. 5) also increased. The probability of observing exceedances in both standards across all sampling locations was greater in the 2009 to 2014 data set than the 2001 to 2008 data set (Fig. 4 and 5). As a result, the 2001 to 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 >90% chance of exceeding the chl-*a* standard twice or more in 5 yr at the Hickory Creek location using the 2001 to 2014 data set (Fig. 4e). However, this probability decreased to approximately 60, 30, and 10% as the number of exceedances for a 5-yr assessment

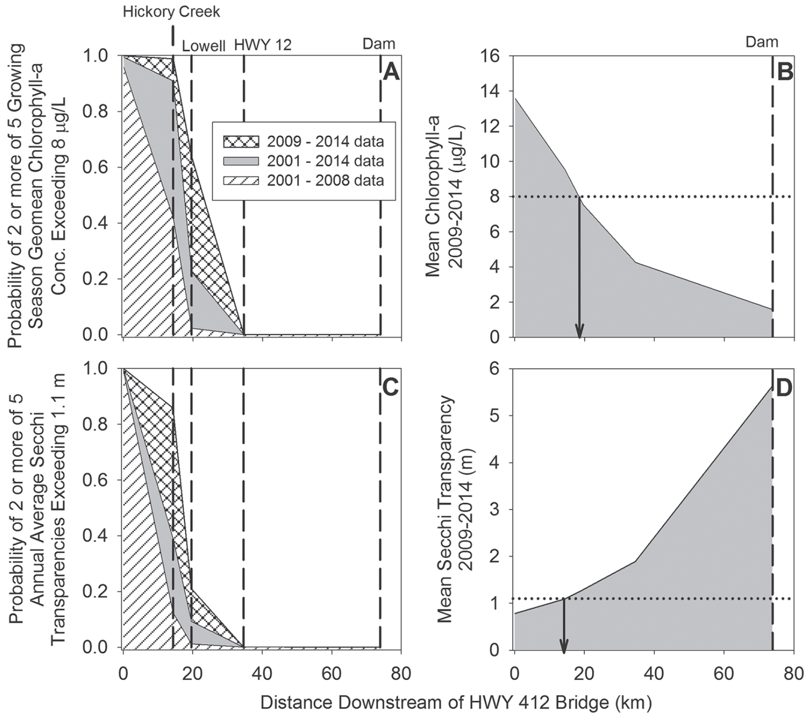

Fig. 3. Probability of exceeding the water quality standards for (A) chlorophyll *a* and (C) Secchi transparency using data collected from 2001 to 2008, 2001 to 2014, or 2009 to 2014, and (B) chl-*a* and (D) ST along the riverine–transition–lacustrine gradient in Beaver Lake. Arrows in (B) and (D) represent the location in Beaver Lake where the chl-*a* and ST values are expected to commonly violate the water quality standards.

period was increased to three or more, four or more, or five, respectively (Fig. 4e).

A 20% probability threshold was used 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 µg L^{-1} growing season geometric mean chl-*a* at Highway 412 was always >20% (Fig. 4a–4c) except when using an exceedance minimum of four or more years across an assessment period of four or more years (Fig. 4a). There was a 20% probability that three in six growing season geometric mean chl-*a* concentrations would exceed 8 µg L^{-1} at Hickory Creek in the 2001 to 2008 data set (Fig. 4d). When using the 2001 to 2014 data set, there was a 20% probability that five in six growing season geometric mean chl-*a* concentrations would exceed 8 µg L^{-1} at Hickory Creek (Fig. 4e). Six of six samples met the 20% probability threshold at the Hickory Creek location with the 2009 to 2014 data set (Fig. 4g). At Lowell, there was never greater than 20% probability of exceeding the chl-*a* standard using the 2001 to 2008 data set (Fig. 4g). However, the 2001 to 2014 data showed a 20% probability of exceeding the chl-*a* standard two or more times in 5 yr (Fig. 4h). There was a 20% probability of having four of six growing season geometric mean chl-*a* exceed 8 µg L^{-1} at Lowell with the 2009 to 2014 data set (Fig. 4i). 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 (Fig. 4j–4l).

The probability of exceeding the 1.1-m annual average ST at Highway 412 was always >20% regardless of the data set, exceedance frequency, or assessment period (Fig. 5a–5c). There was a 20% probability that two in seven annual average STs would exceed 1.1 m in the 2001 to 2008 data set for Hickory Creek (Fig. 5d). 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 to 2014 data set for Hickory Creek (Fig. 5e). Furthermore, the probabilities that ST was <1.1 m greatly increased when using the 2009 to 2014 data set, where there was a 20% probability that three in three exceedances would occur (Fig. 5f). At Lowell, there was never greater than 20% probability of exceeding the ST standard using the 2001 to 2008 data set (Fig. 5g). However, the 2001 to 2014 data showed a 20% probability of exceeding the ST standard two or more times in 7 yr (Fig. 5h), and the 2009 to 2014 data showed a 20% probability of two or more exceedances in 5 yr (Fig. 5i). The probability of exceeding the ST standard at the Highway 12 location never exceeded 20%, regardless of data set, exceedance frequency, or assessment period (Fig. 5j–5l).

Discussion

The objective of this study was to hindcast the compliance of Beaver Lake water quality with the state-mandated water quality standards for chl-*a* and ST to recommend assessment methodology options that are consistent with the justifications for standard development. As predicted, there was a relatively high probability that the growing season geometric mean chl-*a* concentrations and annual average ST would violate the water quality standards in the riverine zone of Beaver Lake and a relatively low probability of violations in the lacustrine zone. The rate of change in exceedance probabilities along the riverine–transition–lacustrine gradient in Beaver Lake was striking, and there was a clear temporal increase in violations when limiting data to those collected since the standards were adopted. Considering that the adopted standards reflected an approximate average long-term water quality condition at the Hickory Creek location in Beaver Lake, it is not surprising that two or more violations in a 5-yr assessment period were common in these simulated assessments.

Based on these results, we recommend that the minimum number of exceedances (i.e., growing season geometric mean chl-*a* >8 µg L^{-1} or annual average ST <1.1 m) 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 probably 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 in this study. As an alternative, we have offered other considerations that would minimize the risk of listing the lake as impaired in an immediate assessment.

Assessment Method Justification

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 Associates, 2008), which effectively positioned the monitoring location in the river–reservoir transition zone (Fig. 1). As

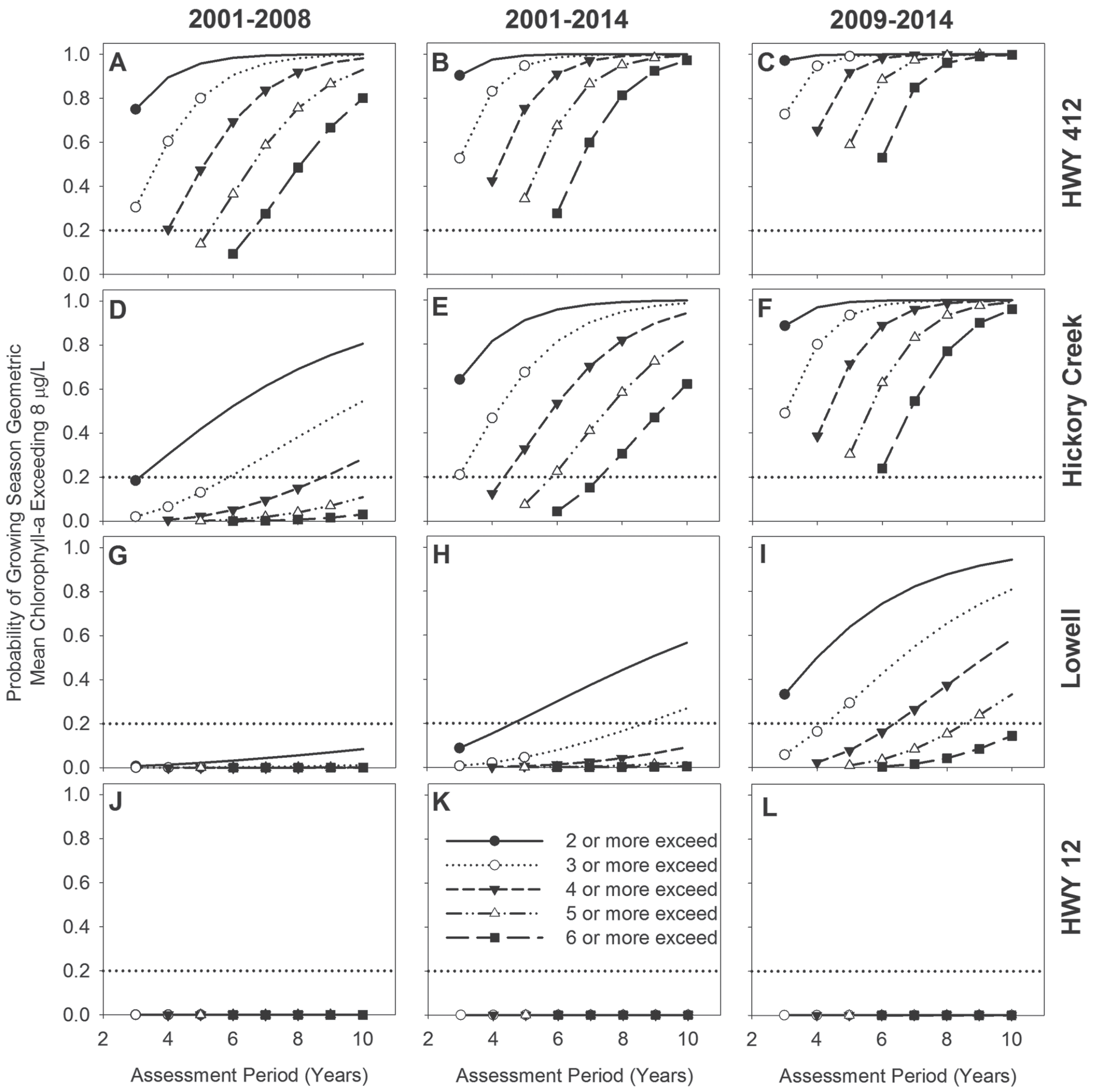

Fig. 4. Probability of exceeding the 8 µg L^{-1} growing-season geometric mean chlorophyll *a* standard, where the number of exceedances is varied across a variable assessment period for Highway 412 using (A) 2001 to 2008 data, (B) 2001 to 2014 data, and (C) 2009 to 2014 data; Hickory Creek using (D) 2001 to 2008 data, (E) 2001 to 2014 data, and (F) 2009 to 2014 data; Lowell using (G) 2001 to 2008 data, (H) 2001 to 2014 data, and (I) 2009 to 2014 data; and Highway 12 using (J) 2001 to 2008 data, (K) 2001 to 2014 data, and (L) 2009 to 2014 data.

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. Although the standards were developed by 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 (see supplemental material). 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.

From a human health perspective, there is a need to link nutrients, phytoplankton biomass, and the potential degradation of water quality associated with increased lake productivity. For example, the production of the cyano-toxin microcystin has been linked to elevated nutrients (Scott et al., 2013) and chl-*a* >1 to 14 µg L^{-1} (Yuan et al., 2014). Similarly, taste-and-odor compounds are typically greater when cyanobacterial phytoplankton have greater biomass (Winston et al., 2014). Greater organic C in water can also lead to increased disinfection byproducts (DBP) following water treatment. Chlorophyll-*a* >4 to 6 µg L^{-1} has been shown to increase DBP to unacceptable levels in water distribution systems (Callinan et al., 2013). Although these water quality outcomes directly affect human health, source water standards are needed that link back to basic nutrient concentrations in waterbodies to inform watershed management (Jarvie et al., 2013; Sharpley et al., 2014).

Whether or not a lake is supporting its drinking water designated use can be readily identified by whether or not municipal water providers have been able to meet their drinking water standards using conventional treatment processes. Beaver Water District (BWD), 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 an unconventional treatment technique to address Stage 2 treatment criteria for DBP (USEPA, 2010b) that was implemented in 2013. Beaver Water District added ClO_2 as a pretreatment oxidant to decrease DBP levels in their distribution system. If this treatment option had not been added, DBP levels would

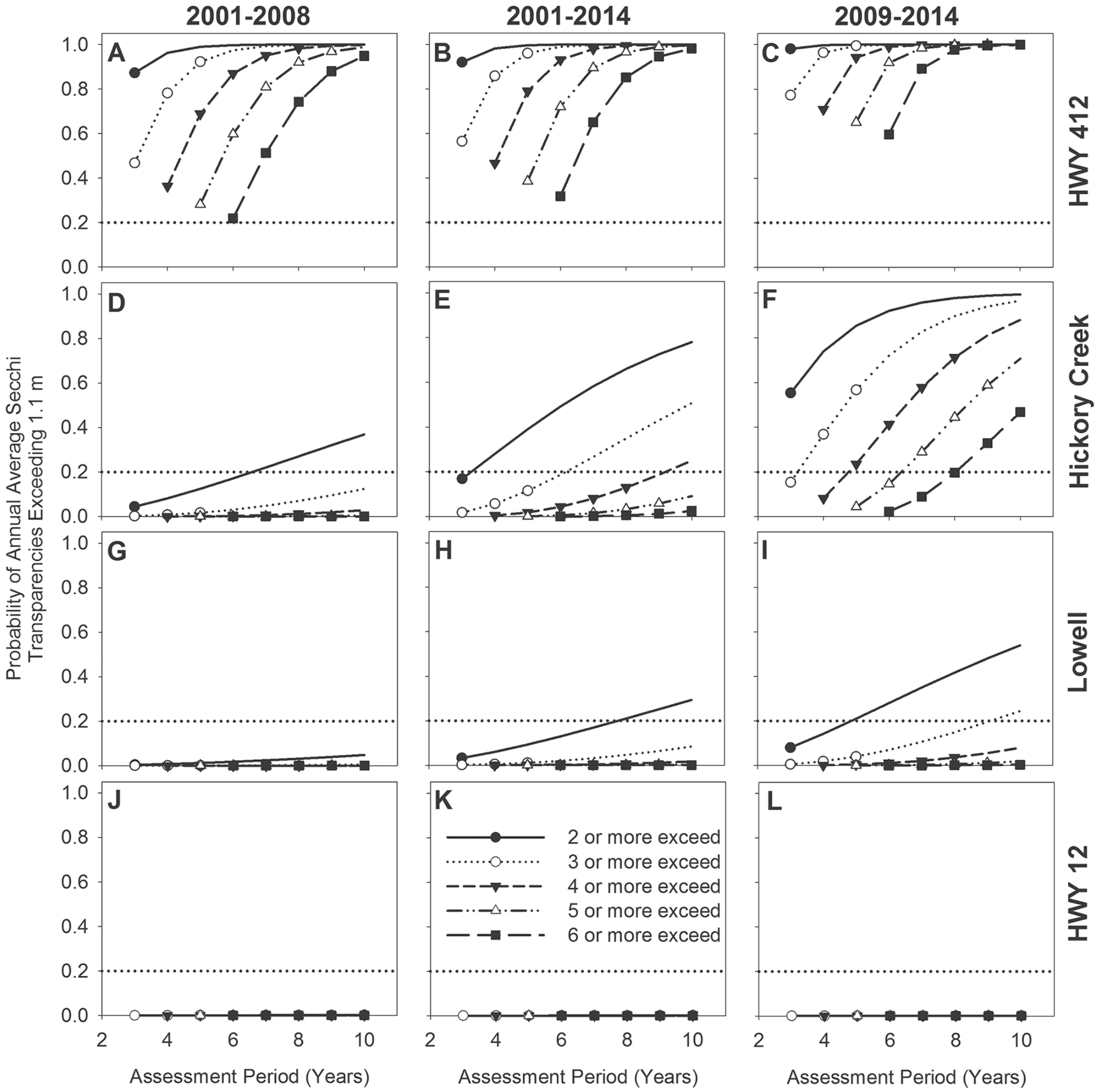

Fig. 5. Probability of exceeding the 1.1-m average annual Secchi transparency standard, where the number of exceedances is varied across a variable assessment period for Highway 412 using (A) 2001 to 2008 data, (B) 2001 to 2014 data, and (C) 2009 to 2014 data; Hickory Creek using (D) 2001 to 2008 data, (E) 2001 to 2014 data, and (F) 2009 to 2014 data; Lowell using (G) 2001 to 2008 data, (H) 2001 to 2014 data, and (I) 2009 to 2014 data; and Highway 12 using (J) 2001 to 2008 data, (K) 2001 to 2014 data, and (L) 2009 to 2014 data.

probably 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 DBP 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 DBP, increased by only 0.05 μg L^{-1} for every 1 μg L^{-1} 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 dissolved organic C and other related chemical characteristics of the Beaver Lake source water. For example, TCM formation potential at 8 μg L^{-1} chl-*a* varied from <90 to >160 μg L^{-1} across the different experiments during 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 BWD. Taken together with the results of our study, this information suggests that Beaver Lake is supporting its current designated use but at a treatment cost that is greater than what has historically been necessary.

The assessment criteria recommended here were based on the information and methods used to develop the chl-*a* and ST standards initially (FTN Associates, 2008). However, in adopting 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. Choosing the recommended minimum allowable exceedances (3 out of 5 yr, 4 out of 7 yr, 5 out of 9 yr, or 6 out of 11 yr) will probably 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 that would not immediately result in water quality violations for Beaver Lake.

Other Options

A number of other 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. Further, to our knowledge no drinking water standards were violated in periods when our hindcasts indicated that Beaver Lake may not have been in compliance with in-lake water quality standards at the Hickory Creek location. Thus, these options also offer possibilities for decreasing the risk of exceeding the criteria based on how the growing season geometric mean chl-*a* and annual average ST data are assessed.

Lengthen the Assessment Period

Five-year assessment periods are common throughout the United States, and the use of more than one violation in a 5-yr period suggests a 40% loss of use, which the Arkansas Department of Environmental Quality often relies on in assessment (personal communication, 2014). However, we have demonstrated in this study that one violation in a 5-yr assessment is inappropriate because the adopted standards were equivalent to the 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 values measured at the Hickory Creek location in Beaver Lake exceeded the water quality standards. Multiple studies have indicated that decadal-scale trends in chl-*a* in lakes may be related to climatic variability (Arhonditsis et al., 2004; Hampton et al., 2008). Assuming that Beaver Lake conforms to a similar pattern, the use of a longer assessment period that approaches or exceeds a decade in length (9 or 11 yr) may capture the full range of potential chl-*a* variation due to climate variability.

Regulatory agencies could also consider using a rolling or moving average of the yearly geometric mean chl-*a* during the growing season and annual average ST, which might "smooth" the variability in the data driven by climatic patterns, lake management, or anthropogenic factors. However, smoothing via rolling averages has only a minor effect on the absolute value of chl-*a* and ST. Moreover, the probabilities that approximately half of the years in an assessment period will exceed the criteria remain high with this approach.

Couple the Standards

The chl-*a* and ST were probably intended to be considered as separate, and 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. The growing season geometric mean chl-*a* concentration and annual average ST at Hickory Creek are strongly related because the 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.

Revise 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 arithmetic average, respectively, 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. The probability-of-exceedance analysis presented in 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 5 yr at Lowell would be within the desired risk (20% or less). When using a 5-yr moving average, there was a 10% or less risk that two or more exceedances would occur in 5 yr for chl-*a* or ST (data not shown). 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 and subsequent approval by the state legislature.

Data and Analysis Limitations

The probability analyses used to derive assessment methodologies in this project require relatively long-term data and assume no directional change during the period of record. It is important to note that both of these requirements had to be stretched 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 Associates, 2008) was used to calculate the 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 with time at this location. What remains unknown is whether or not these trends were driven by changes in the watershed (Gémesi et al., 2011) or by long-term climate-based variability (Arhonditsis et al., 2004; Hampton et al., 2008). For the purposes of this project, we simply acknowledge this trend observed at a single monitoring location. We also put more weight on data collected before 2008 when the water quality standards were adopted.

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 Associates, 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 ($R^2 = 0.55, p < 0.001$). Because standard development relied on a regression equation with poor predictive power, 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. The exceedance probabilities at Hickory Creek fell between the exceedance probabilities at the Highway 412 location and Lowell (Fig. 3) so the estimates should be reasonably realistic. Nevertheless, the chl-*a* and ST standards for Hickory Creek should be re-evaluated when sufficient data (>10 yr) are available.

Substantial changes in water quality can occur over a decade or more due to water quality management at the watershed scale (Scott et al., 2011). Although the Lowell location was the only one for which growing season geometric mean chl-*a* and annual average ST were changing with 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. Nevertheless, our analysis demonstrates that while the water quality standards adopted for Beaver Lake were justified based on multiple lines of scientific evidence, the likelihood of the monitoring data exceeding these standards has increased in recent years. The recommended assessment method integrates these patterns into a scientifically defensible approach for determining the water quality status of Beaver Lake.

Study Implications

The results of this study demonstrate the importance of linking water quality standard development with commonly used assessment methodologies by states. These considerations should occur before standard development to ensure that promulgated standards are compatible with the assessment period and method adopted by state regulatory agencies. Our study demonstrates that this is particularly important for numeric nutrient criteria and effects-based numeric criteria for nutrients because there can be tremendous natural variation in these parameters in lakes. In fact, nutrient concentrations, chl-*a*, and ST in lakes can exhibit tremendous interannual variation due to annual river flows and climate conditions. Unlike toxic substances or pathogens, the deleterious effects of nutrients and elevated algal biomass are sometimes less clear, particularly at low or moderate input levels. Thus, states and the USEPA should consider that any science used to develop statewide, regional, or site-specific nutrient criteria also include recommendations regarding assessment methodologies that would best reflect the conditions that the standards are intending to protect.

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