Utah Lake Water Quality Study—Approaches for Developing Numeric Nutrient Criteria: A Literature Review

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PRESENTED TO

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Cover image: Aerial View of Provo Utah with River Valley and Utah Lake, by Aqua Mechanical. Source file available at https://www.flickr.com/photos/aquamech-utah/24776739750/in/photostream/

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ABBREVIATIONS

Abbreviation	Definition
BHM	Bayesian hierarchical modeling
BLR	Bayesian latent variable regression
BTPM	biological thresholds and predictive modeling
BTreed	Bayesian Treed
EFDC	Environmental Fluid Dynamics Code
HSPF	Hydrological Simulation Program–FORTRAN
IBI	index of biological integrity
LASSO	least absolute shrinkage and selection operator
LSPC	Loading Simulation Program C
MEI	morphoedaphic index
nCPA	nonparametric changepoint analysis
RCA	Row-Column AESOP
RMA	ranged major axis
SNAPIT	State Nitrogen and Phosphorus Information Tool
TITAN	Threshold Indicator Taxa ANalysis
TMDL	total maximum daily load
TN	total nitrogen
TP	total phosphorus
UMR–LP	Upper Mississippi River–Lake Pepin
USEPA	United States Environmental Protection Agency
WASP	Water Quality Analysis Simulation Program

1.0 BACKGROUND

The goal of the Utah Lake Water Quality Study is to evaluate the role of excess nutrients in the support of designated uses in Utah Lake, with a focus on development of in-lake water quality criteria that are protective of the lake's designated uses. The goal of this literature review is to evaluate applicable approaches for developing numeric nutrient criteria for Utah Lake. Because this review focuses on methods of deriving water quality criteria, aquatic ecosystems other than lakes were considered.

2.0 SEARCH AND SCREENING STRATEGY

Tetra Tech built off our existing collection of nutrient criteria development efforts, literature reviews, state mutually agreed upon nutrient criteria development plans, and the State Nitrogen and Phosphorus Information Tool (SNAPIT) database. SNAPIT is a database that Tetra Tech maintains internally which includes total maximum daily load (TMDL) studies where numeric nutrient targets were developed. SNAPIT is currently under development and not publicly available. We supplemented this information with additional peer-reviewed and white papers relevant to numeric nutrient threshold derivation approaches.

For the additional literature, Tetra Tech developed the following search and screening strategy for peer-review and technical reports relevant to numeric nutrient threshold derivation approaches. The Web of Science Core Collection ("Topic" field) databases were searched, in addition to Google and Google Scholar. Because the existing literature reviews cover older research, search results were sorted by date, and the most recent 50 results from each search was reviewed for relevancy. This review focuses on criteria development approaches, and most of the existing older research on this topic is captured by existing review.

The following search terms were used:

1. (Shallow lake) AND (nitrogen OR phosphorus OR phosphorous OR nutrient) AND (criteria OR threshold OR target)
2. "lake nutrient criteria"
3. (wetland OR river OR stream) AND (nitrogen OR phosphorus OR phosphorous OR nutrient) AND (criteria OR threshold OR target)

The first set of search terms was intended to target papers and reports that address shallow lakes specifically, and the second to target a potentially smaller number of relevant papers and reports that address lake nutrient criteria in general (i.e., not specific to shallow lakes). The third set of search terms was used to cast a wider net for potentially unique approaches from other aquatic systems that may be relevant. Unique approaches to numeric nutrient criteria development for other types of water bodies such as wetlands, rivers, and streams were also covered through the inclusion of materials from Tetra Tech's existing collection of nutrient criteria development efforts across those different water bodies.

The titles and/or abstracts of each search result were reviewed, and inclusion criteria were used to determine the relevancy of each search result:

- Results were included if they are not already cited in an existing nutrient criteria review document that will be referenced in the current literature review.
- The result must address nutrient criteria development in water bodies.
- The result must include enough information on the approach to understand the details.
- Only results written in English were considered.

Results that were determined to be relevant were obtained through available library resources and stored digitally. All relevant search results are managed in a reference database.

In addition to the above search and screening strategy, the following review papers and reports were referenced:

- Nutrients in Lakes and Reservoirs—A Literature Review for Use in Nutrient Criteria Development (VWRRC 2007)
- Texas Nutrient Criteria Development Support Project (Environmental Institute of Houston 2011)
- Approaches to Setting Nutrient Targets in the Red River of the North (Plevan and Blackburn 2013)
- Development of Methods for Establishing Nutrient criteria in Lakes and Reservoirs: A Review (Huo et al. 2018)

3.0 APPROACHES FOR DEVELOPING NUTRIENT CRITERIA

Various approaches to developing numeric nutrient criteria are discussed in the literature. Whereas much of the focus on nutrient criteria development was originally based on establishing a reference condition for water bodies (e.g., *Nutrient Criteria Technical Guidance Manual, Lakes and Reservoirs* [USEPA 2000a]), more recently the focus has shifted to include other approaches such as empirical stressor-response modeling (e.g., *Using Stressor-response Relationships to Derive Numeric Nutrient Criteria* [USEPA 2010]) and the use of mechanistic models to link concentrations to desired endpoints such as dissolved oxygen concentrations or limited cyanobacteria presence (e.g., Carleton et al. 2009). Numeric nutrient targets are often developed as part of total maximum daily load (TMDL) efforts (USEPA 1999) and are also included in this review.

The primary approaches for developing nutrient criteria are using reference water bodies, empirical stressor-response modeling, mechanistic stressor-response modeling, and the use of literature values. Each of these approaches is discussed here, and examples from the literature are provided.

Many of the numeric nutrient criteria development efforts cited in this literature review involve multiple lines of evidence where more than one approach is used, and the results are integrated to derive the final criteria (e.g., Heiskary and Wilson 2008, VWRRC 2007).

3.1 REFERENCE

A lake's reference condition ideally describes the state of the lake in the absence of, or under minimal, anthropogenic influence. However, because it can be difficult to find undisturbed lakes, the reference condition typically describes the least impacted condition of a lake or the most attainable condition. The United States Environmental Protection Agency's (USEPA's) *Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs* (USEPA 2000a) describes three approaches to establishing the reference condition:

- Direct observation (data collection) of sites and estimation or inference of reference conditions
- Paleolimnological reconstruction of past conditions
- Model-based prediction or extrapolation of reference conditions

Each approach is discussed in detail below.

Direct observation (data collection) of sites and estimation or inference of reference conditions

Using this approach, the distribution of data from a collection of reference lakes can be used to infer the reference condition. Alternatively, data from an entire population of lakes (i.e., not just reference lakes) are assessed, and the 25th percentile of the distribution is assumed to represent the reference condition. This approach was used by the USEPA (2001) in recommending nutrient criteria for lakes and reservoirs in nutrient ecoregion III, subecoregion 13, which is where Utah Lake is located. Studies often calculate statistics using multiple approaches and compare the results. For example, Suplee et al. (2007) evaluated the frequency distribution method with a dataset from Montana streams. They found high variability, with the 75th percentile of the reference set of streams corresponding to the 4th to 97th percentile of the general population.

Other reports and papers that used statistical summaries of monitoring data to describe the reference condition include Ohio EPA (2010), Dodds et al. (2006), and Bachman et al. (2012), but none of these reported any innovations relative to the USEPA guidance method described above. Since temporal data within a lake can be correlated, different statistical approaches including extreme value theory have been used to remove this effect and a lower percentile of long-term values in a time series used to estimate reference condition for a single lake (Wang et al. 2018).

Comparison of a water body to one or more reference sites is also often used to develop nutrient targets for TMDL estimates (USEPA 1999). USEPA recommends that, for TMDLs, the set of reference lakes should be similar to the lake of interest in morphology, land use/cover, climate, and elevation, but should be minimally impacted.

The reference condition of tributaries that flow into the lake of interest can be viewed as an upper limit of the nutrient reference condition of the lake, because nutrients typically are lower in lakes than in influent waters.The USEPA (2000b) published reference conditions for nutrient ecoregion III, subecoregion 13; this document provides the 25th percentile nutrient concentrations for the entire population of rivers and streams (USEPA 2000b).

These approaches are all population-based approaches, in that the refernce condition of a lake is inferred from the distributation of data from a population of lakes.

Paleolimnological reconstruction of past conditions

The remains of certain types of organisms are often preserved in lake sediments. If a relationship (e.g., pH or phosphorus optima) between water quality endpoints and biota exists, this relationship can be applied to the biological remains to infer past lake water quality conditions. Diatom frustules and chrysophyte scales have been used most often to reconstruct past water quality conditions; other groups of organisms that have been used include sponges, bryozoa, cladocera, and chironomid larvae (Paul and Gerritsen 2002). Diatom-inferred pre-European total phosphorus concentrations were used by the Minnesota Pollution Control Agency to provide information on background conditions by ecoregion as part of a multiple lines of evidence approach to deriving numeric criteria for lakes in Minnesota (Heiskary and Wilson 2005, Heiskary and Wilson 2008, Heiskary and Swain 2002). Diatom-inferred total phosphorus concentrations were also used to develop a site-specific standard for a lake in south-central Minnesota (MPCA 2015).

Paleolimnological data from a single lake can be used to infer the reference condition of that lake; see MPCA (2015) as an example. Alternatively, data from a population of reference lakes can be used to infer the reference condition for a geographic region and/or lake type. This population-based approach was used by Heiskary and Wilson (2005, 2008).

Weaknesses in the use of diatom-inferred total phosphorus concentrations can limit the utility of these models (Juggins et al. 2013). The relationship between phosphorus and diatom abundances can be confounded with other variables such as alkalinity and lake depth, the inference models may contain diatom taxa that are not significantly related to total phosphorus, and, lastly, there is often poor or no spatial replicability among different models.

Model-based prediction or extrapolation of reference conditions

If little limnological data are available to determine a lake's reference condition, other approaches can be used to predict the reference condition using empirical or mechanistic models. USEPA (2000a) describes the morphoedaphic index (MEI) to estimate reference conditions. The MEI is the ratio of total dissolved solids in lake water to the mean lake depth. The MEI approach (Vighi and Chiaudani 1985) is a relatively simple approach that predicts lake phosphorus concentrations resulting from natural background nutrient loading. This approach was applied to Florida lakes (Paul and Gerritsen 2002), but it was determined not to be an appropriate approach for developing nutrient criteria in Florida lakes.

Other types of empirical models can be used to predict the reference condition. As part of a multiple lines of evidence approach, Cardoso et al. (2007) developed a general linear model to predict reference total phosphorus (TP) concentration with data from a group of 567 European lakes that were considered to be in reference condition. The independent explanatory variables in the model were selected by Pearson correlations and included altitude, mean depth, and alkalinity; MEI was also considered. An empirical model to predict the concentrations of stream solutes expected under reference conditions in western United States streams was developed with multiple linear regression and random forest models (Olson and Hawkins 2012).

As part of a biological thresholds and predictive modeling (BTPM) approach for lakes in Michigan, Soranno et al. (2008) estimated lake reference TP concentration using stepwise multiple regression to model lake TP as a function of hydrogeomorphic features and human land use and land cover data. The least disturbed expected condition was predicted by setting the human land use and land cover coefficients to zero. An allowance, which was based on the upper 75th confidence interval of the regression model, was added to the expected condition to account for model uncertainty; the allowance could also account for a minimal level of allowable human disturbance. Dodds et al. (2006) also used a regression-based extrapolation in which the y-intercept predicted lake nutrient concentration in the absence of anthropogenic influence. These approaches are all population-based models.

For the Pearly Lake TMDL in New Hampshire (AECOM and NH Department of Environmental Services 2014), the ENSR–LRM model (a land use export coefficient model for use in New England) was used in conjunction with empirical lake models to simulate watershed and lake phosphorus concentrations. A natural background scenario was developed to predict the lake phosphorus concentration of Pearly Lake under natural environmental background conditions; this phosphorus concentration was used as the TMDL target.

Mechanistic models have also been used to identify reference conditions by constructing models and backcasting a period of relatively higher water quality (Zhang et al. 2018) or by setting watershed loads to forested conditions and simulating the nutrient and response conditions (Camacho et al. 2014).

In the TMDLs for Lake Alma and Lake Searcy in Florida (Rhew 2018, Tetra Tech 2017a, Tetra Tech 2017b), Hydrological Simulation Program–FORTRAN (HSPF), Environmental Fluid Dynamics Code (EFDC), and Water Quality Analysis Simulation Program (WASP) models were used to simulate lake water quality under natural background conditions. Land use in the HSPF watershed model was modified to reflect undisturbed conditions, and the simulated flows and water quality loads were linked with the EFDC and WASP models. For Lake Alma, the 80th percentile of the natural background chlorophyll-*a* concentration was selected as a site-specific TMDL target.

The Charlotte Harbor Hydrodynamic and Water Quality Model is a linked Loading Simulation Program C (LSPC), EFDC, and WASP model that simulates nutrients, organic matter, and dissolved oxygen in impaired water bodies in Charlotte Harbor, Florida (USEPA Region 4 2009). Similar to the Lake Alma and Lake Searcy natural background simulations, a natural condition scenario was developed in which developed land uses were replaced with forest land uses in the LSPC watershed model. The LSPC-simulated flow and water quality conditions were used as inputs to the EFDC model, which was then run and used as inputs to the WASP model. Whereas nutrient targets were not derived in this study using the natural conditions scenario, this type of modeling approach can be used for that purpose.

These mechanistic modeling examples address single water bodies as opposed to population-based approaches.

3.2 EMPIRICAL STRESSOR-RESPONSE MODELING

The USEPA's technical guidance, *Using Stressor-response Relationships to Derive Numeric Nutrient Criteria* (USEPA 2010), details a four-step approach to developing and interpreting stressor-response relationships to derive phosphorus and nitrogen numeric criteria:

1. **Conceptual models** are developed to illustrate accepted scientific knowledge about the effects of nitrogen and phosphorus in surface waters. Causal pathways that link human activities, nutrient inputs, and impacts to designated uses in lakes and streams are incorporated into conceptual models. By identifying relationships that can be evaluated with statistical models, conceptual models guide the development of stressor-response models. Conceptual models also identify potential confounding variables and therefore include alternate causal pathways that may not be related to nutrients.
2. **Exploratory data analysis** evaluates data to understand relationships, suggest statistical modeling approaches, and evaluate the basis for statistical modeling assumptions. Variables from the conceptual model are selected and include variables that can be directly linked with designated uses, in addition to potentially confounding variables. Data are then assembled and analyzed to describe the distribution of the variables and how variables covary with one another.
3. **Stressor-response relationships** between nitrogen and phosphorus and the selected response variables are developed to identify appropriate criteria. First, classification of water bodies into groups with similar characteristics is recommended to control for possible effects of naturally confounding variables (e.g., lake size or color). After classification, simple linear regression is used to estimate stressor response relationships that are easily interpreted for derivation of criteria. If the assumptions of simple linear regression are too restrictive, other statistical modeling approaches can be used, such as multiple linear regression, quantile regression, nonparametric regression curves, and nonparametric changepoint analysis. Stressor-response models are typically population-based models in which criteria are derived from a population of water bodies.
4. To estimate the scientific defensibility of the stressor-response relationships and criteria derived from them, the **model accuracy and precision** is evaluated. Potential confounding variables are systematically assessed to evaluate the model accuracy. The required model precision depends on the management context and how the criteria will be used.

Some authors have used stressor-response modeling in the context of external factors such as climate change and multiple stable states. Liu et al. (2018) used empirical stressor-response modeling to derive numeric nutrient criteria for lakes in Heilongjiang Province, China, and evaluated if climate change is expected to change the relationship between stressor and response variables and therefore the numeric nutrient criteria derived from the relationship. Differences among climate change factors were evaluated with analysis of covariance. In a study of shallow lakes in Minnesota, Vitense et al. (2018) used Bayesian latent variable regression (BLR) to estimate critical phosphorus thresholds with respect to chlorophyll and multiple stable states in shallow lakes.

Empirical stressor-response modeling can take many forms. If a chlorophyll-*a* target exists, nitrogen or phosphorus targets can be derived from a linear regression (e.g., Chambers et al. 2011), and typical linear regression with interpolation to desired response conditions is a recommended approach (USEPA 2010). As part of a multiple lines of evidence approach to develop nutrient criteria for Florida lakes, USEPA (n.d.) derived total nitrogen (TN) and TP criteria from chlorophyll-*a* targets using linear regression. The baseline criteria were defined as the upper 50th percentile prediction intervals around the regression line. Similarly, as part of the state of Mississippi's effort to develop nutrient criteria for lakes and reservoirs, chlorophyll-*a* thresholds were derived from the relationship of chlorophyll to diurnal dissolved oxygen, and then nitrogen and phosphorus targets were derived from linear regression with chlorophyll-*a* (Tetra Tech 2013). Simple linear models have been extended to include multiple predictors and even multilevel effects. For example, in developing nutrient criteria for lakes, ponds, and reservoirs, Freeman et al. (2009) used a Bayesian Treed (BTreed) model approach. They developed regional eutrophication models using hierarchical techniques that use the empirical linear model of nutrients and chlorophyll as the terminal node of tree models and simultaneously classify lakes into regional classes based on a variety of predictors.

The response targets for linear models that use interpolation to identify nutrient targets can be existing criteria, derived themselves from other stressor-response models (e.g., of dissolved oxygen as a function of chlorophyll-*a*), or from literature (e.g., trophic states). Relating user surveys of water body use support to water quality is also used to derive response targets and is included by USEPA (1999) as a method of deriving numeric nutrient criteria. User surveys were used by the state of Vermont to derive phosphorus criteria for Lake Champlain (Smeltzer 1999), were part of a weight of evidence approach to derive lake phosphorus criteria in Minnesota lakes (Heiskary and Walker 1988, Heiskary and Wilson 2005, Heiskary and Wilson 2008), were used to evaluate the relationship between algal level and aesthetic impairment in Montana (Suplee et al. 2009) and Utah (Jakus et al. 2017) water bodies, and were used in a Bayesian configuration to link public satisfaction with water quality conditions in the Bay of Quinte, Ontario, Canada (Ramin et al. 2018). The Bay of Quinte effort also used expert elicitation (Kim et al. 2018). Structural equation modeling has been similarly used to relate expert elicited opinions of water quality goal attainment to observed water quality measurements (Reckhow et al. 2005, Kenney et al. 2009, Su et al. 2017). Also involving professional opinion, one component of the state of Virginia's development of reservoir nutrient criteria involved biologists' rankings of lake fishery status in relationship to chlorophyll and phosphorus concentrations (VWRRC 2007).

Quantile linear regression, in which a line is fit to a statistic other than the means of the response variable, is often used when dealing with wedge-shaped data or data for which the constraint on the response may not be best represented by the mean (Cade and Noon 2003). The outer portions of the probability distribution represent conditions under which the stressor variable limits the response variable. Bryce et al. (2008) related pre-determined index of biological integrity (IBI) goals to sediment concentration in streams of the western United States; sediment targets that correspond to the IBI goal then were determined with quantile regression.

Biological thresholds exist in systems where a small increase in a stressor leads to an abrupt change in the biological response. Stressor-response modeling techniques such as regression tree analysis (Lougheed et al. 2007, Soranno et al. 2008, Zheng et al. 2008, and Wang et al. 2007); nonparametric changepoint analysis (nCPA; Cao et al. 2016, Cao et al. 2017, Huo et al. 2015); and Threshold Indicator Taxa ANalysis (TITAN; Cao et al. 2016, Cao et al. 2017, Taylor et al. 2014, Taylor et al. 2018) can identify the stressor level at which a biological threshold exists. TITAN and nCPA are techniques that identify ecological community thresholds. TITAN distinguishes negative and positive responses of individual taxa, resulting in narrower confidence intervals than those identified with multivariate changepoint analysis (Baker and King 2010, Baker and King 2013, King and Baker 2014). Uncertainty around the identified biological threshold in all of these techniques is often assessed using bootstrap resampling. Grantz et al. (2018) used changepoint analysis to calculate water quality targets for reservoirs in Texas. As part of the analysis, multiple methods were used to handle censored data. They found that the method used to censor observations can affect the targets identified in changepoint analysis.

Similarly, a recursive partitioning analysis technique was used by the Interstate Commission on the Potomac River Basin (2011) to identify confounding factors and identify breakpoints in a study of the relationship between nutrients and biological responses (phytoplankton, periphyton, and macroinvertebrates) in Maryland streams and rivers.

Analysis of data from the National Lakes Assessment has used empirical stressor-response modeling to relate chlorophyll-*a* concentrations to the extent of hypoxia in lakes across the country (Yuan and Pollard 2015a), to relate TN and TP to cyanobacterial biovolume (Yuan and Pollard 2015b), and to relate nitrogen and chlorophyll-*a* concentrations to microcystin concentration (Yuan et al. 2014). Yuan et al. (2014) used least absolute shrinkage and selection operator (LASSO) regression to identify variables that best predict high concentrations of microcystin. Results from these types of studies could also be used to develop numeric nutrient targets.

Nutrient bioassays, a form of experimental stressor-response development, can be used to both establish limiting nutrients as well as relationships between nutrient concentration and algal biomass in a water body, and this relationship can support nutrient target development. Potential nutrient targets for Lake Waco, Texas, were developed in this manner (Kiesling et al. 2001). Phosphorus was determined to limit algal biomass production in the lake, and dose-response bioassays then were used to develop a predictive relationship between phosphorus and algal biomass. Biomass-based algal growth rates were calculated using a simple exponential growth model and fit to a Monod function. A candidate target was developed using the Monod models based on the phosphate concentration that will reduce algal biomass by up to 50 percent. Another candidate target was identified from a scatterplot of algal biomass from the nutrient bioassays versus phosphate concentration; a threshold was identified visually from the relationship. Nutrient bioassays can also take the form of limnocorrals in lakes (Heard and Sickman 2016).

Other types of empirical relationships between chlorophyll-*a* and nutrients can serve as the basis of numeric nutrient criteria derivation. In the El Dorado Park Lakes TMDLs in Los Angeles (USEPA 2012), the Nutrient Numeric Endpoints Bathtub Tool was used to determine the nitrogen and phosphorus concentrations that correspond to the predetermined chlorophyll goal. Chlorophyll targets can be derived using the approaches described in this literature review; see Yuan and Pollard (2015a) as an example.

Stressor-response modeling approaches are often used in a multiple lines of evidence context. For example, in an effort to develop nutrient criteria for the major shallow lakes in Europe, Poikane et al. (2019) applied four methods that modeled the relationship between lake macrophyte ecological condition and nutrients (total phosphorus and total nitrogen). The methods were ranged major axis (RMA) regression, multivariate regressions, and two categorical approaches—logistic regression and minimizing mis-match of classifications. For both the RMA (univariate) and multivariate regressions, the potential range of criteria was determined by the upper and lower quartiles of the regression residuals, and uncertainty was estimated from these quartiles. Huo et al. (2015) integrated several nonparametric approaches to identify ecological nutrient response thresholds—classification and regression tree, nonparametric changepoint analysis, and a Bayesian hierarchical modeling (BHM) method. A Bootstrap simulation was used to identify 90 percent confidence intervals.

3.3 MECHANISTIC MODELING

In addition to using mechanistic modeling to simulate the reference condition (Section 3.1), mechanistic modeling can also be used to link nutrient concentrations to desired endpoints such as dissolved oxygen concentrations or limited cyanobacteria presence. There are a multitude of such examples, including some very high profile systems (e.g., Great Lakes, Chesapeake Bay, San Francisco Bay, Long Island Sound); here we highlight only a few examples.

A multiple lines of evidence approach that included mechanistic modeling was used to develop site specific eutrophication criteria for Lake Pepin, a run of the river lake along the Mississippi River on the Minnesota–Wisconsin state border. A linked hydrodynamic sediment transport water quality model was developed to support the Upper Mississippi River–Lake Pepin (UMR–LP) TMDLs (DePinto et al. 2009). The model framework is based on modified versions of two public domain models—the ECOMSED hydrodynamic/sediment transport model and the Row-Column AESOP (RCA) water quality model. Model scenarios predicted frequencies of algal blooms and percent cyanobacteria in Lake Pepin under different loading and flow conditions. A lake phosphorus concentration target was selected that minimizes the frequency of nuisance blooms and the percent cyanobacteria in the algal assemblage. Other lines of evidence were diatom-inferred phosphorus concentrations from approximately 1900–1960 (Engstrom and Almendinger 2000), expected ecoregion-based inflow phosphorus concentrations, protection of downstream waters, and the state of Wisconsin's intended phosphorus criteria for Lake Pepin (MPCA 2011).

A mechanistic aquatic ecosystem model, AQUATOX, was applied to a reach of the Blue Earth River, Minnesota, to simulate changes in biological indexes (i.e., percentage cyanobacterial biomass of sestonic algae and benthic chlorophyll-*a*) as a result of changing phosphorus, nitrogen, and suspended sediment inputs (Carleton et al. 2009). Stressor-response scatterplots were visually examined to identify a phosphorus threshold below which percent cyanobacteria abruptly dropped.

With predetermined pH, dissolved oxygen, and benthic algae concentration goals, Flynn and Suplee (2011) used a river and stream water-quality model (QUAL2K) application to determine where along the nitrogen and phosphorus concentration gradient the Lower Yellowstone River in Montana would become impaired for these water quality parameters. Uncertainty was quantified with Monte Carlo simulations as the mean deviation of possible Monte Carlo outcomes.

Watershed loading and estuary water quality models were developed for the Santa Margarita River Estuary, California, to inform nutrient management (Sutula et al. 2016). Watershed loads were simulated with HSPF, and receiving water models were developed with EFDC and WASP. The models were used to summarize the major pathways that supply nutrients to the estuary, estimate the range of allowable loads, evaluate the link between the selection of numeric targets and the allowable loads, and inform nutrient management. As part of the evaluation, the relationships between nutrient loading and dissolved oxygen concentrations were evaluated, and the load reductions needed to meet a dissolved oxygen and a macroalgal biomass target were assessed. Nutrient targets were not developed for the estuary; it was determined that nitrogen and phosphorus concentrations are not strongly linked to beneficial uses. However, the type of modeling approach used in this study could be applied to that purpose.

3.4 LITERATURE—PUBLISHED

When enough data are not available on the water body of interest to derive criteria with site-specific data, nutrient criteria that have been developed and published in the literature for other similar systems can be used (USEPA 1999). Literature values should be used only if sufficient evidence is presented that the literature-based target is suitable to the water body of interest. The water body of interest must have characteristics similar to the systems that were used to derive the published targets (USEPA 2000c).

The total phosphorus standard for Lahontan Reservoir in Nevada was determined through a combination of literature values and empirical modeling (Cooper and Vigg 1983, Pahl 2012). The chlorophyll threshold of 10 µg/L was based on literature values that indicate algae concentrations that impair beneficial uses. An empirical relationship in the reservoir between phosphorus and chlorophyll was then used to derive the phosphorus target. The state of Virginia, in developing phosphorus criteria for reservoirs, considered a weight of evidence approach (VWRRC 2007). One of the pieces of evidence involved relationships between fisheries health and phosphorus and/or chlorophyll concentrations presented in the literature. In *Summary of Scientific Literature Relevant to Wyoming Lake/Reservoir Nutrient Criteria* (Tetra Tech 2009), a range of nutrient levels from the literature is provided to be used as part of the development of lake nutrient criteria in Wyoming. Other approaches were explored for reservoirs and involve targets for trophic state boundaries from the literature.

3.5 SUMMARY TABLE OF APPROACHES

Table 1 lists the cited references and categorizes them according to the approach used to derive numeric nutrient targets.

Table 1. List of references and approaches

Reference	Reference: Direct Observation	Reference: Paleo-limnological	Reference: Model	Empirical Stressor-Response Modeling	Mechanistic Stressor-Response Modeling	Literature
Baker and King 2013				x		
Dodds et al. 2006	x					
AECOM and NH Department of Environmental Services 2014			x			
Bachman et al. 2012	x					
Baker and King 2010				x		
Bryce et al. 2008				x		
Cade and Noon 2003				x		
Camacho et al. 2014			x		x	
Cao et al. 2016				x		
Cao et al. 2017				x		
Cardoso et al. 2007			x			
Carleton et al. 2009					x	
Chambers et al. 2011				x		
Cooper and Vigg 1983						x
DePinto et al. 2009					x	
Dodds et al. 2006			x			
Engstrom and Almendinger 2000		x				
Flynn and Suplee 2011						
Freeman et al. 2009				x		
Grantz et al. 2018				x		
Heard and Sickman 2016				x		
Heiskary and Swain 2002		x				
Heiskary and Walker 1988				x		
Heiskary and Wilson 2005		x		x		
Heiskary and Wilson 2008		x		x		
Huo et al. 2015				x		
Interstate Commission on the Potomac River Basin 2011				x		
Jakus et al. 2017				x		
Juggins et al. 2013		x				
Kenney et al. 2009				x		
Kiesling et al. 2001				x		
Kim et al. 2018				x		
King and Baker 2014				x		
Liu et al. 2018				x		

Reference	Reference: Direct Observation	Reference: Paleo-limnological	Reference: Model	Empirical Stressor-Response Modeling	Mechanistic Stressor-Response Modeling	Literature
Lougheed et al. 2007				x		
MPCA 2015		x				
Ohio EPA 2010	x					
Olson and Hawkins 2012			x			
Pahl 2012						x
Paul and Gerritsen 2002		x	x			
Poikane et al. 2019				x		
Ramin et al. 2018				x		
Reckhow et al. 2005				x		
Smeltzer 1999				x		
Soranno et al. 2008			x	x		
Su et al. 2017				x		
Suplee et al. 2007	x					
Suplee et al. 2009				x		
Taylor et al. 2014				x		
Taylor et al. 2018				x		
Tetra Tech 2009						x
Tetra Tech 2013				x		
Tetra Tech 2017a			x			
Tetra Tech 2017b			x			
USEPA n.d.				x		
USEPA 2000b	x					
USEPA 2001	x					
USEPA 2012				x		
Utah DWQ 2005	x					
Vighi and Chiaudani 1985			x			
Vitense et al. 2018				x		
VWRRC 2007				x		x
Wang et al. 2007				x		
Wang et al. 2018	x					
Whitmore and Brenner 2002		x				
Whitmore and Riedinger 2002		x				
Yuan and Pollard 2015a				x		
Yuan and Pollard 2015b				x		
Zhang et al. 2018			x		x	
Zheng et al. 2008				x		

4.0 STATE PLANS FOR NUMERIC NUTRIENT CRITERIA DEVELOPMENT

States and territories have submitted numeric nutrient criteria development plans for review and approval by the USEPA. A selection of the plans for states closest to Utah that have been mutually agreed upon by the states and the USEPA were reviewed to determine the technical approach that the state intends on using to develop its numeric nutrient criteria. Of the nine reviewed, eight plan on using empirical stressor-response modeling, two plan on using mechanistic modeling, six plan on incorporating a reference condition, and five will use literature values (Table 2). Many of the states plan on using multiple lines of evidence.

Table 2. Approaches to numeric nutrient criteria derivation in state mutually agreed upon development plans

Mutually Agreed Upon State Plan	Empirical Stressor-Response Modeling	Mechanistic Stressor-Response Modeling	Reference Condition	Literature Values
Arizona/Nevada/CA (Tetra Tech 2002)	x	x	x	
Colorado (Colorado Department of Public Health and Environment 2002)	x			
Idaho (IDEQ 2007)	x		x	x
Montana (Montana DEQ 2002)	x	x	x	x
Nevada (NDEP 2007)	x			
New Mexico (NMED 2006)			x	x
New Mexico (NMED 2014)	x			x
Utah (Utah DWQ 2005)	x		x	
Wyoming (Wyoming DEQ 2008)	x		x	x

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