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Development of a Screening Tool To Examine Lake and Reservoir Susceptibility to Eutrophication in Selected Watersheds of the Eastern and Southeastern United States

Scientific Investigations Report 2021–5075

U.S. Department of the Interior
U.S. Geological Survey

Cover. A harmful algal bloom in a New York lake. Photograph by the U.S. Geological Survey.

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U.S. Geological Survey, Reston, Virginia: 2021

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Suggested citation:
Green, W.R., Hoos, A.B., Wilson, A.E., and Heal, E.N., 2021, Development of a screening tool to examine lake and reservoir susceptibility to eutrophication in selected watersheds of the eastern and southeastern United States: U.S. Geological Survey Scientific Investigations Report 2021–5075, 59 p., https://doi.org/10.3133/sir20215075.

Associated data for this publication:
Heal, E.N., and Green, W.R., 2021, Nutrient loading, flushing rate, and lake morphometry data used to identify trophic states in selected watersheds of the eastern and southeastern United States: U.S. Geological Survey data release, https://doi.org/10.5066/P9K7EOH0.

ISSN 2328-0328 (online)

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)

Supplemental Information

Concentrations of chemical constituents in water are either given in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

EPA	U.S. Environmental Protection Agency
SPARROW	SPAtially-Referenced Regression On Watershed attributes
TSI	Carlson’s Trophic State Index
USGS	U.S. Geological Survey

Development of a Screening Tool To Examine Lake and Reservoir Susceptibility to Eutrophication in Selected Watersheds of the Eastern and Southeastern United States

By W. Reed Green,[1] Anne B. Hoos,[1] Alan E. Wilson,[2] and Elizabeth N. Heal[1]

Abstract

This report describes a new screening tool to examine lake and reservoir susceptibility to eutrophication in selected watersheds of the eastern and southeastern United States using estimated nutrient loading and flushing rates with measures of waterbody morphometry. To that end, the report documents the compiled data and methods (R-script) used to categorize waterbodies by Carlson's Trophic State Index. Assessments were completed for 232 lakes and reservoirs having a surface area greater than or equal to 0.1 square kilometer in watersheds that drain to the Atlantic and eastern Gulf of Mexico coasts of the United States and in watersheds within the Tennessee River Basin. Waterbodies were categorized by type—natural lakes, headwater reservoirs, and downstream reservoirs—and were assessed independently. Recursive partitioning and the model-based boosting routine were used to create four-node regression trees to group waterbodies into five endpoints from low-to-high measures of Secchi depth, and concentrations of chlorophyll *a* and microcystin according to shared nutrient loading, flushing rate, and morphometric characteristics. Trophic state designations were assigned based on the average value within each of the five endpoints. An application (procedure) is provided using the tool to examine the susceptibility of a given waterbody of interest to eutrophication. Results of this study can aid water-resource managers in prioritizing lake and reservoir protection and restoration efforts based on the susceptibility of these waterbodies to eutrophication relative to nutrient loading, flushing rate, and morphometric characteristics.

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Introduction

For Federal and State agencies and other water-resource managers, determining which waterbodies to allocate resources for protection and restoration, while maximizing cost benefit, is challenging. Over the years, several empirical models have been developed and used for forecasting or predicting concentrations of nutrients and chlorophyll *a*, Secchi depths, and trophic state in lakes and reservoirs (Dillon, 1975; Vollenweider, 1976; Canfield and Bachman, 1981), each requiring a measure of nutrient load (typically phosphorus), lake basin morphometry (mean depth), and hydrology (flushing rate or retention time). More recently, Beaver and others (2014), Knoll and others (2015), and Read and others (2015) have used results from the U.S. Environmental Protection Agency (EPA) National Lake Assessment (U.S. Environmental Protection Agency, 2009, 2016) to examine landscape (landcover), morphometric variables (surface area, mean depth, and maximum depth), and lake characteristics (sediment area-to-volume ratio) as predictors of water quality and trophic state.

Estimated nutrient loads are available for lakes, reservoirs, and estuaries for all watersheds draining to the Atlantic and eastern Gulf of Mexico coasts of the United States, and for watersheds in the Tennessee River Basin (Hoos and others, 2013; Moorman and others, 2014). Lake and reservoir morphometric measures also are available for these same waterbodies (Hollister and Milstead, 2010; Hollister and others, 2011). Measures of Secchi depth and concentrations of chlorophyll *a* and the cyanotoxin microcystin are available in the EPA National Lake Assessment 2007 and 2012 program databases (U.S. Environmental Protection Agency, 2009, 2016) for 232 of the U.S. Geological Survey (USGS) SPARROW (SPAtially-Referenced Regression On Watershed attributes) nutrient load waterbodies with EPA lake and reservoir morphometric measures, and a surface area greater than 0.1 km^2 within the study area. Given the availability of these nutrient loading and morphometrics data, along with flushing rate calculations, we hypothesize that the predictability of trophic status, the susceptibility to eutrophication, and the potential for the occurrence of the cyanotoxin microcystin in these lakes and reservoirs can be improved and better specified using multivariate analysis and machine-learning tools, specifically, recursive partitioning and model boosting.

The purpose of this report is to describe a new screening tool to examine lake and reservoir susceptibility to eutrophication in selected watersheds of the eastern and southeastern United States using estimated nutrient loading and flushing rates with measures of waterbody morphometry. To that end, the report documents the compiled data and methods (R-script) used to categorize waterbodies by Carlson's Trophic State Index (TSI). By placing the selected waterbodies into these categories, water-resource managers in these locations can identify lakes and reservoirs that are likely most or least susceptible to eutrophication. Data tables for these waterbodies are provided in Heal and Green (2021).

Description of Study Area

The study area includes 232 lakes and reservoirs in the National Hydrography Dataset that have a surface area greater than 0.1 km^2 and are either in watersheds that drain to the Atlantic and eastern Gulf of Mexico coasts of the United States, or in watersheds within the Tennessee River Basin (fig. 1; Hoos and others, 2013). Those lakes and reservoirs included in the EPA National Lake Assessment 2007 and 2012 programs were selected for study. Data from the following waterbodies were used in this study: 65 lakes, 121 headwater (dammed) reservoirs, and 46 downstream reservoirs, those with reservoirs or dams upstream. These waterbodies are classified herein using the following criteria: lakes have no control structure regulating water-surface elevation, headwater reservoirs have no upstream control structures, and downstream reservoirs have upstream control structures.

Most of the lakes were in the northeastern United States, with Maine having the most (19), followed by Vermont (8), New Hampshire (7), Connecticut (6), Massachusetts (5), New York (4), Pennsylvania (2), and Rhode Island (2). Elsewhere, nine lakes were in Florida, two were in Maryland, and one was in North Carolina. There were no oxbow lakes in this dataset.

Headwater reservoirs were distributed throughout 16 states, with Virginia having the most (19), followed by Pennsylvania (14), Alabama (11), Rhode Island (10), North Carolina (9), Connecticut (8), Georgia (8), Delaware (6), Maine (6), Maryland (6), New Hampshire (6), New Jersey (6), Massachusetts (5), South Carolina (4), New York (2), and Florida (1).

Downstream reservoirs were distributed throughout 16 states as well, with North Carolina having the most (12), followed by Alabama (5), Maine (4), Delaware (4), Connecticut (3), New Jersey (3), Pennsylvania (3), South Carolina (2), Tennessee (2), Virginia (2), Florida (1), Georgia (1), Massachusetts (1), Mississippi (1), New Hampshire (1), and Rhode Island (1).

At least one measurement of Secchi depth and (or) concentration of chlorophyll *a* and (or) microcystin was available for each of the 232 waterbodies. Often, data were available from both the 2007 and 2012 National Lake Assessments, some waterbodies having multiple sampling data from and including May through September of a given year. As such, this assessment includes discrimination among the different waterbodies within each group (lakes, headwater reservoirs, and downstream reservoirs) and within each waterbody for those waterbodies having more than one datapoint.

Description of Datasets

USGS SPARROW Model Estimates of Nutrient Loading

The USGS modeling tool SPARROW relates instream water-quality measurements to spatially referenced characteristics of watersheds, including contaminant sources and factors influencing terrestrial and aquatic transport. The SPARROW model empirically estimates the origin and fate of contaminants in river networks and quantifies uncertainties in model predictions (Schwarz and others, 2006). Estimates from the eastern U.S. SPARROW model (Hoos and others, 2013) of 2002 annual nutrient loads in streams (1:100,000-scale hydrography) draining to the Atlantic and eastern Gulf of Mexico coasts of the United States, and streams within the Tennessee River Basin, were used to determine nutrient loads for all 41,566 lakes, reservoirs, and estuaries in these watersheds (Moorman and others, 2014). At the time of report preparation, these lakes, reservoirs, and estuaries were the only ones that had SPARROW nutrient loading data. This is the reason waterbodies were only assessed within areas draining to the Atlantic and eastern Gulf of Mexico coasts of the United States and in watersheds within the Tennessee River Basin.

For this analysis, we used the subset of 7,917 lakes and reservoirs with surface areas greater than or equal to 0.1 km^2. Nutrient-loading estimates from Hoos and others (2013) and Moorman and others (2014) include (1) total nitrogen and total phosphorus annualized flow-weighted concentration of the inflow load estimate, in milligrams per liter; (2) the inflow total nitrogen to total phosphorus annualized flow-weighted concentration ratio of the inflow load estimate; and (3) mean annual outflow, in cubic meters per second, for the reach segment at the downstream end of the lake or reservoir.

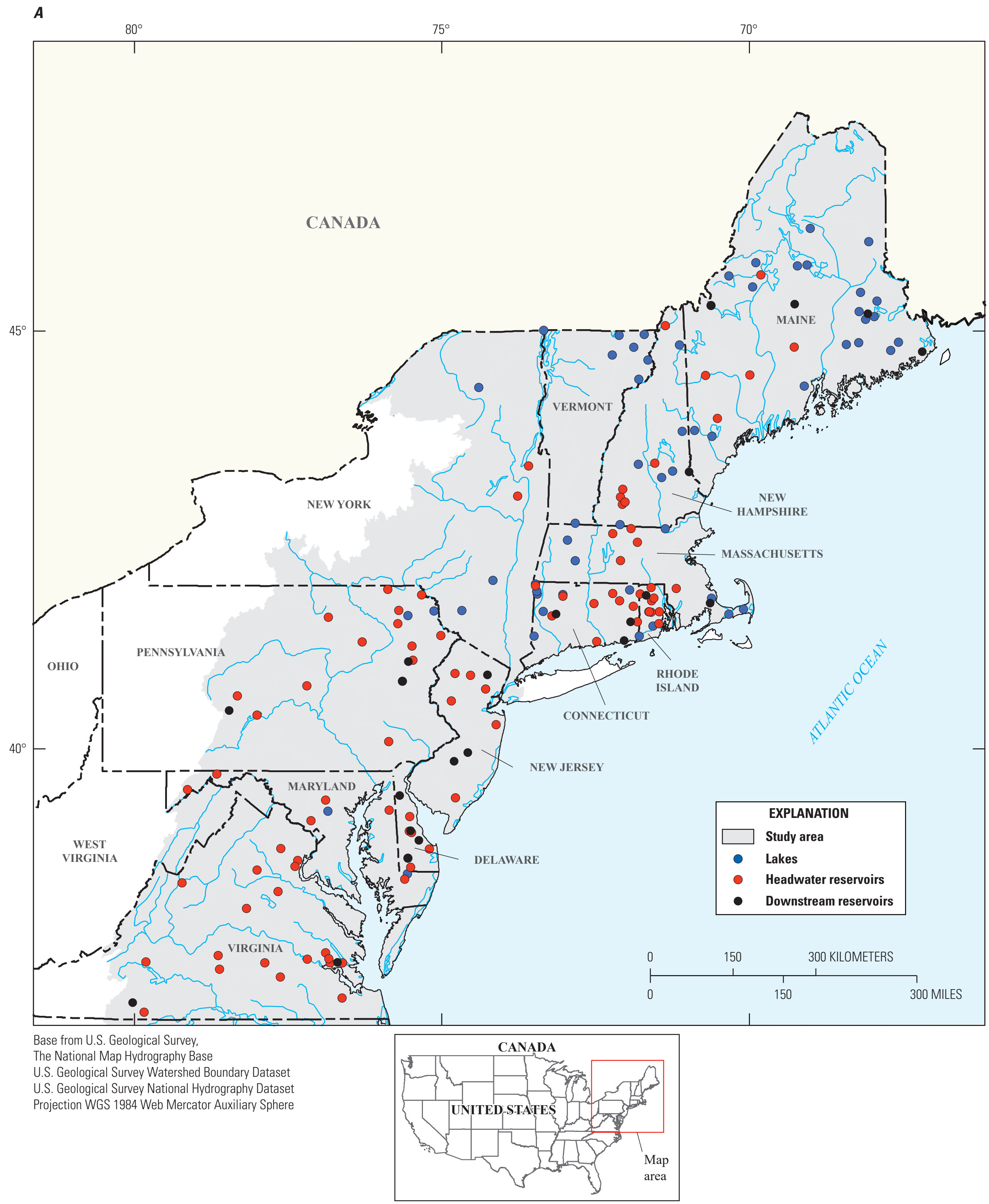


Figure 1. Locations of lakes, headwater reservoirs, and downstream reservoirs for which nutrient loads were determined (Hoos and others, 2013). *A*, North and Middle Atlantic Region. *B*, South Atlantic Region.

B

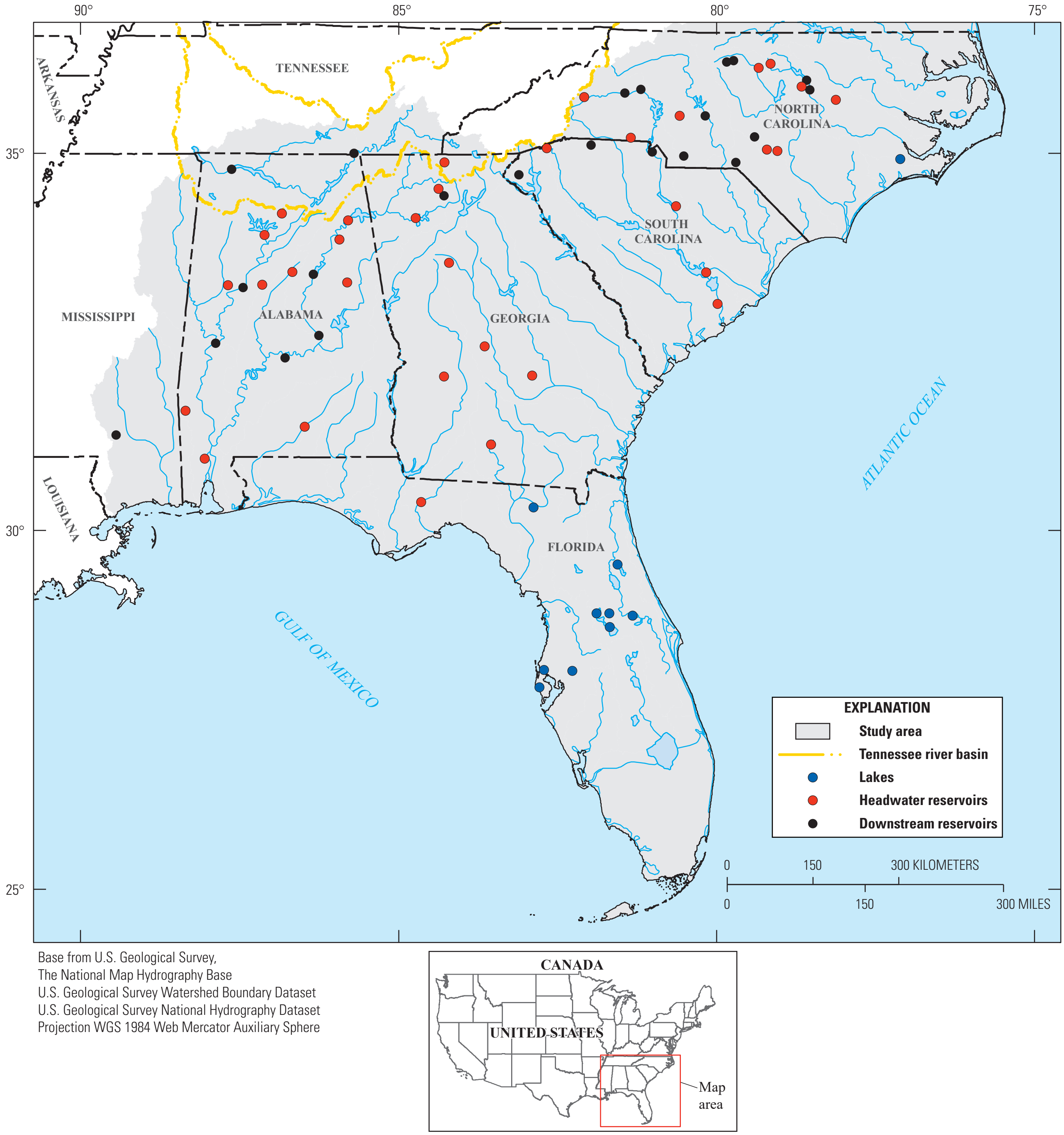


Figure 1. Locations of lakes, headwater reservoirs, and downstream reservoirs for which nutrient loads were determined (Hoos and others, 2013). *A*, North and Middle Atlantic Region. *B*, South Atlantic Region.—Continued

EPA Lake Morphometry Dataset

Lake and reservoir morphometric characteristics—shoreline length, in meters; surface area, in square meters; volume, in cubic meters; maximum depth, in meters; and mean depth, in meters—were selected from the EPA's Facility Registry Service Clip N Ship online application for the National Lake Morphometry dataset (Hollister and Milstead, 2010; Hollister and others, 2011, and U.S. Environmental Protection Agency (2014a, b, c, d, e, f). Lake morphometry shapefiles for the North Atlantic East, Mid Atlantic, South Atlantic North, South Atlantic South, South Atlantic West, and Tennessee hydrologic units were downloaded, and data from those lakes and reservoirs with a surface area greater than or equal to 0.1 km^2 were selected. Lake and reservoir morphometrics were derived from shoreline length, surface area, volume, mean depth, and maximum depth acquired from the National Lake Morphometry dataset, as described below.

Flushing rate (FR)—the annualized displacement of the waterbody volume, derived by dividing the SPARROW mean annual outflow, in cubic kilometers per year, by the lake or reservoir volume, in cubic kilometers, recorded in the EPA National Lake Morphometry Dataset.

Shoreline development ratio (SDR)—represents the shoreline length relative to the length of the circumference of a circle of area equal to the surface area of the lake or reservoir and is calculated as follows (Hutchinson, 1957; Wetzel, 1983; U.S. Army Corps of Engineers, 1987):

$$SDR = \frac{shoreline\ length}{2\sqrt{\pi \times surface\ area}}, \qquad (1)$$

where

shoreline length is the length of the waterbody shoreline, in kilometers; and

surface area is the surface area of the waterbody, in square kilometers.

A value of 1 represents a perfect circle. Large ratios indicate very irregular or dendritic systems. The shoreline development ratio reflects the potential for greater development of the littoral communities in proportion to the volume of the lake (Wetzel, 1983). The littoral zone is the most biologically productive area within a lake or reservoir.

Morphometric factor (MF)—related to the fraction of the reservoir's volume involved in mixis (that is, wind disruption of thermal stratification, breaking down the thermocline) during warm-season stratification and is calculated as follows (Osgood, 1988; Nürnberg, 1995):

$$MF = \frac{mean\ depth}{\sqrt{surface\ area}}, \qquad (2)$$

where

mean depth is the mean depth of the waterbody, in meters.

The closer the morphometric factor is to zero, the more susceptible the waterbody is to wind-driven breakdown of the warm-season thermocline and mixing. The morphometric factor can be viewed as a surrogate for the influence of internal phosphorus loading and algal growth. The lower the value (less than 5) the more susceptible the waterbody is to mixing phosphorus-rich anoxic water below the thermocline up into the solar penetrating surface water (photic zone).

Development of volume (DV)—the difference in the shape of the lake or reservoir from that of a cone with equal maximum depth, volume, and area, and is calculated as follows (Hutchinson, 1957; U.S. Army Corps of Engineers, 1987):

$$DV = 3 \times \frac{mean\ depth}{maximum\ depth}, \qquad (3)$$

where

maximum depth is the maximum depth of the water body, in meters.

A value of 0.33 represents a perfect conical depression. Development of volume is greatest in waterbodies with flat bottoms.

Basin permanence (BP)—the ratio between lake or reservoir volume and shoreline length, calculated as follows (Kerekes, 1977; U.S. Army Corps of Engineers, 1987):

$$BP = \frac{volume}{shoreline\ length}, \qquad (4)$$

where

volume is waterbody volume, in million cubic meters.

The lower the index value (less than 0.1), the shallower (filling in) and less permanent the water body; the higher the index value (0.2 or greater), the more permanent the waterbody. An extinct lake or reservoir would have a value approaching zero.

Relative depth (RD)—the ratio of the maximum depth as a percentage of the "diameter" of the lake or reservoir derived from surface area, calculated as follows (Wetzel, 1983; U.S. Army Corps of Engineers, 1987; Wetzel and Likens, 1991):

$$RD = \frac{50 \times maximum\ depth \times \sqrt{\pi}}{\sqrt{surface\ area}}, \qquad (5)$$

The smaller the relative depth, the greater the influence of wind in disrupting thermal stratification.

Erosion ratio (ER)—the theoretical fraction of the lake or reservoir bed area subject to the processes of scouring, resuspension, and transport, calculated as follows (Håkanson, 1982; U.S. Army Corps of Engineers, 1987):

$$ER = 25\times\left(\frac{\sqrt{surface\ area}}{mean\ depth}\right)\times 41^{\left(\frac{0.061\times mean\ depth}{\sqrt{surface\ area}}\right)}. \quad (6)$$

EPA National Lake Assessment Data

Secchi depth, in meters, and concentrations of chlorophyll *a*, in micrograms per liter, and microcystin, in micrograms per liter, during the growing season months of May through September were selected from the EPA National Lake Assessment 2007 and 2012 datasets (U.S. Environmental Protection Agency 2009, 2016) for those lakes and reservoirs having a surface area greater than 0.1 km^2 within the SPARROW model area of coverage. Of the 7,917 lakes and reservoirs meeting these criteria in the SPARROW dataset, 232 lakes and reservoirs could be associated with waterbodies in the EPA National Lake Assessment. These lakes and reservoirs were separated into three functional types: lakes, headwater reservoirs, and downstream reservoirs. Altogether, 297 Secchi depth measurements, 315 chlorophyll *a* samples, and 280 microcystin samples were reported among the 232 lakes and reservoirs (table 1). Methods for the EPA National Lake Assessment sample collection and analysis are described in U.S. Environmental Protection Agency (2016).

Carlson's Trophic State Index

Carlson's Trophic State Index (TSI; Carlson, 1977) is a widely used measure of eutrophication status of a given lake or reservoir and is based on the natural logarithm (ln) of measured Secchi depths and concentrations of chlorophyll *a* and total phosphorus. The TSI values for measured Secchi depth and chlorophyll *a* concentrations (EPA National Lake Assessment data) were calculated for each waterbody using equation 7 below for Secchi depth and equation 8 for chlorophyll *a* concentration (Carlson and Simpson, 1996):

$$\mathrm{TSI}(SD) = 60 - 14.41\times\ln(SD)\ , \quad (7)$$

$$\mathrm{TSI}(CHL) = 9.81\times\ln(CHL) + 30.6\ , \quad (8)$$

where

SD is Secchi depth, in meters; and

CHL is chlorophyll *a* concentration, in micrograms per liter.

Table 1. U.S. Environmental Protection Agency National Lake Assessment sample numbers for measures of Secchi depths and concentrations of chlorophyll *a* and microcystin by waterbody type (lakes, headwater reservoirs, and downstream reservoirs) used in this study.

[m, meter; µg/L, micrograms per liter]

Statistic	Lakes	Headwater reservoirs	Downstream reservoirs
Secchi depth (m)			
Count	80	158	59
Maximum	8.6	9.6	6.8
Minimum	0.1	0.3	0.3
Mean	2.7	2.3	1.8
Median	2.5	1.6	1.4
Chlorophyll *a* (µg/L)			
Count	91	164	60
Maximum	197	216	196
Minimum	0.73	0.40	0.83
Mean	20.1	18.2	24.0
Median	4.21	6.07	9.78
Microcystin (µg/L)			
Count	78	147	55
Maximum	6.3	18.3	1.22
Minimum	0.01	0.01	0.01
Mean	0.03	0.40	0.12
Median	0.01	0.07	0.05

As eutrophication in a lake or reservoir increases, leading to greater potential of harmful algal blooms and cyanotoxins, the Secchi depth, chlorophyll *a*, and total phosphorus TSI numbers will increase as a result. In general, along the continuum between 0 and 100, a TSI value less than 30 indicates oligotrophy, characterized by clear water that is oxygenated throughout the year in the hypolimnion. In shallower lakes and reservoirs, the hypolimnion may become anoxic. A value between 30 and 50 indicates mesotrophy, characterized by water that is moderately clear and an increasing probability of hypolimnetic anoxia during the summer. A value between 50 and 70 indicates eutrophy, characterized by anoxic hypolimnia, possible macrophyte problems, cyanobacteria that may dominate the phytoplankton community, and algal scums. A value between 70 and 100 indicates hypereutrophy, characterized by light that becomes limiting for algae growth due to dense cyanobacterial blooms and algal scums. Based on Secchi depth measures and concentrations of chlorophyll *a* and total phosphorus, lakes and reservoirs can be grouped into one of seven trophic-state categories: oligotrophic, oligo-mesotrophic, mesotrophic, meso-eutrophic, eutrophic, eutro-hypereutrophic, and hypereutrophic. More information about the interpretation of trophic state is available in Carlson and Havens (2005).

Validation Dataset

An independent dataset of Secchi depth measures and concentrations of chlorophyll *a* from lakes and reservoirs in the southeastern United States was made available from a USGS Water Resources Research Institute project conducted at the Wilson Lab at Auburn University in Auburn, Ala. This was a joint project between Auburn University and various State agencies in the southeastern United States responsible for monitoring and assessing ambient water quality following EPA approved procedures and guidelines. Chlorophyll *a* was analyzed and Secchi depths were measured by the cooperating State agencies. Data were requested from these State agencies from their routine ambient lake monitoring programs (freshwater lakes, reservoirs, large rivers, and ponds) visited in July or August 2012, 2013, and 2014. Altogether, 149 Secchi depths and 150 chlorophyll concentrations were provided by the State agencies from 62 lakes, 74 headwater reservoirs, and 34 downstream reservoirs within the SPARROW nutrient loading model area of coverage.

Methods

SPARROW-based estimates of total nitrogen and total phosphorus annualized flow-weighted concentrations of the inflow load estimate, total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate, flushing rate, and the six waterbody calculated morphometrics (shoreline development ratio, morphometric factor, development of volume, basin permanence, relative depth, and erosion ratio) described above were included in data mining routines to partition lakes and reservoirs of similar Secchi depths and concentrations of chlorophyll *a* and microcystin. The total nitrogen and total phosphorus annualized flow-weighted concentrations of the inflow load estimates were used instead of total nitrogen and phosphorus load or total nitrogen and total phosphorus areal load to remove the difference in inflow volume between waterbodies (larger drainage basin runoff will naturally be larger than smaller drainage basins) and better represented nutrients contributed by watershed attributes.

Waterbodies were classified as lakes (having no outflow control structure), headwater reservoirs (having a control structure at the outflow, but no upstream control structure[s]), and downstream reservoirs (having a control structure at the outflow and control structure[s] upstream). These classifications were made individually by visual assessment using the online digital satellite imagery mapping applications Google Earth and Google Maps.

Recursive Partitioning

Recursive partitioning is a tool used for data mining, for exploring the structure of a dataset, and for producing rules to predict categorical or continuous outcomes visually in the form of a classification or regression tree (Therneau and Atkinson, 2019). The R Project for Statistical Computing software (R Foundation, undated) for recursive partitioning and regression trees package *rpart* (Therneau and others, 2019) was used to produce partition-tree models that at the end, grouped together lakes and reservoirs having similar Secchi depths and concentrations of chlorophyll *a* and microcystin. Results (endpoint groupings) were based on (1) predicted nitrogen and phosphorus inflow concentrations, (2) the ratio of nitrogen to phosphorus inflow concentrations, (3) flushing rates, and (4) six different waterbody morphometrics.

The *rpart* programs build classification models that are represented as binary trees; the leaves are the partitioned nodal endpoints. The *rpart* algorithm first examines all possible splits for all covariates and chooses the split that leads to two groups that are "purer" than the current group with respect to the values of the response variables (Everitt and Hothorn, 2010)—Secchi depth and concentrations of chlorophyll *a* and microcystin in the case of this study. Splits continue to be generated until recursion meets the criterion to stop, and that criterion was to produce a four-node, five-endpoint tree.

Model-Based Boosting

Model boosting (*mboost*), an add-on package in The R Project for Statistical Computing software data (Hothorn and others, 2018a) was used interactively to fit the recursive partitioning results. Model boosting is described as a functional gradient descent algorithm for optimizing general risk functions utilizing component-wise (penalized) least-squares estimates or regression trees as base-learners for fitting generalized linear, additive, and interaction models to potentially high-dimensional datasets (Bühlmann and Hothorn, 2007).

Summary Statistics and Regression Trees

Partykit is an add-on package in The R Project for Statistical Computing software (Hothorn and others, 2018b) that was used to summarize the statistics and produce the regression tree plots (shown later). The *partykit* toolkit provides a flexible platform for learning, representing, summarizing, and visualizing a wide range of tree-structured regression and classification models (Hothorn and Zeileis, 2015). *Partykit* was used, along with *rpart* and *mboost*, to generate the regression trees' resulting endpoints (leaves)—groupings of water bodies with similar Secchi depths and concentrations of chlorophyll *a* and microcystin—following the example provided in Everitt and Hothorn (2010, p. 164–167).

The modeling (regression tree) objective was to identify the most sensitive parameters and relations between parameters using recursive partitioning and model boosting that drive Secchi depths and concentrations of chlorophyll *a* and microcystin in the study lakes and reservoirs by holding the models to four splits (nodes), producing five leaves or (nodal) endpoints. Holding the regression trees to four nodes and five endpoints was forced so as not to over-parameterize or under-parameterize the models. This was achieved by "pruning" through the R function *minsplit*, the minimum number of observations in a node for which the routine will try to compute a split (Therneau and Atkinson, 2019). *Minsplit* numbers were manually adjusted to achieve the four-node, five-endpoint output.

Method of Analysis

Concentrations of chlorophyll *a* and microcystin were log-transformed (base10) for analysis because of their log-normal distribution. Mean values reported in regression tree figures, tables, and the text herein were determined by averaging the log-transformed values and then taking the antilog to convert the value back into a linear concentration.

An example of a five-endpoint chlorophyll *a* regression tree for headwater reservoirs is shown in figure 2. The branching pattern shows that total phosphorus flow-weighted concentration of the inflow load estimate (*TP_CONC_inload*) drives the first nodal split at 0.062 milligrams per liter (mg/L); it is the heaviest weighted variable in the multivariate analysis. The second heaviest weighted variable is total nitrogen flow-weighted concentration of the inflow estimate (*TN_CONC_inload*), splitting at 1.903 mg/L. *BP* was the third heaviest weighted variable, splitting at a value of 0.335. *MF* was not the fourth heaviest weighted variable; it was eighth in the multivariate analysis ranking. However, because of the recursive partitioning, model boosting, and pruning process rules, *MF* was determined to be the parameter for the fourth split below *TP_CONC_inload* less than 0.062 mg/L and a *BP* value less than 0.335, and it splits at a value of 4.7. The five endpoints, from left to right, are identified as one through five in the discussion of the results that follows. The boxplots within each endpoint represent the data distribution of the selected waterbodies. The mean and median values are listed below the individual boxplots, as well as the number of individual waterbodies represented and the TSI designations for either Secchi depth or chlorophyll *a*, depending on which parameter is plotted. In the case of microcystin, the Secchi depth, chlorophyll *a*, and total phosphorus TSI designations are included.

Each of the partition plots presented herein are followed by tables for each endpoint listing the waterbodies within each endpoint, their outlet latitude and longitude, along with the parameter values for the respective independent variables (nodes). The TSI value for each waterbody is included for the EPA National Lake Assessment-recorded Secchi depth or chlorophyll *a* concentration(s). If more than one measurement of Secchi depth or chlorophyll *a* concentration was available for a given waterbody, values were averaged to provide one representative TSI value. The number of values averaged in such cases is shown in parentheses following the lake or reservoir name; for example, "Spring Creek Lake (2)." For microcystin results, TSI values for the EPA National Lake Assessment recorded Secchi depths, chlorophyll *a*, and total phosphorus are included.

Examination of Lake and Reservoir Susceptibility to Eutrophication

The resultant regression trees are shown for Secchi depths, in meters, and concentrations of chlorophyll *a* and microcystin, in micrograms per liter. For each measurement type, lake results are presented first, followed by results for headwater reservoirs, and lastly, results for downstream reservoirs.

Secchi Depths

Lakes

Of the 56 lakes characterized by 80 Secchi depth observations, 9 lakes were classified as eutro-hypereutrophic, 7 eutrophic, 24 mesotrophic, and 16 oligo-mesotrophic (fig. 3). Basin permanence was the highest weighted variable (21 percent), followed by relative depth (14 percent), flushing rate (12 percent), morphometric factor (12 percent), erosion ratio (10 percent), total phosphorus flow-weighted concentration of the inflow load estimate (10 percent), total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate (8 percent), total nitrogen flow-weighted concentration of the inflow load estimate (6 percent), shoreline development ratio (5 percent), and development of volume (5 percent). The model-boosting functional gradient descent algorithm separated the recursive partitioning tree into four nodes and five endpoints by using the minimum number of observations in a node considered for splitting, which was set at 25.

Details of the lakes identified within each endpoint are included in tables 2–6. The individual Secchi depth or mean Secchi depth (in the case where two or more Secchi depths were recorded) for each lake was converted to the TSI value for Secchi depth (eq. 7) for validation. In addition, the Secchi depths for each endpoint were averaged and assigned a TSI designation, fig. 3).

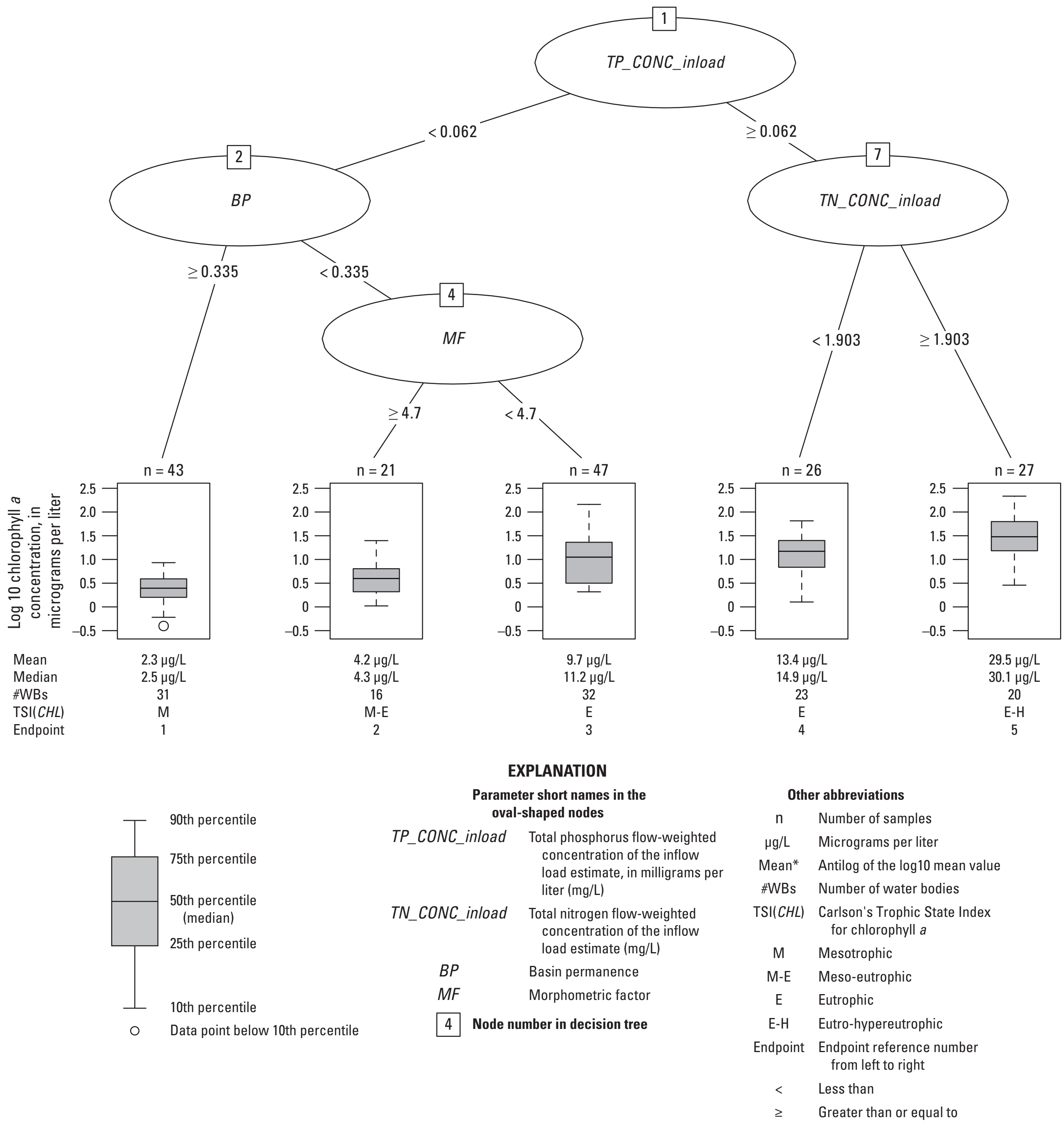


Figure 2. Diagram showing an example of a regression tree breakdown for log base 10 chlorophyll *a* for headwater reservoirs.

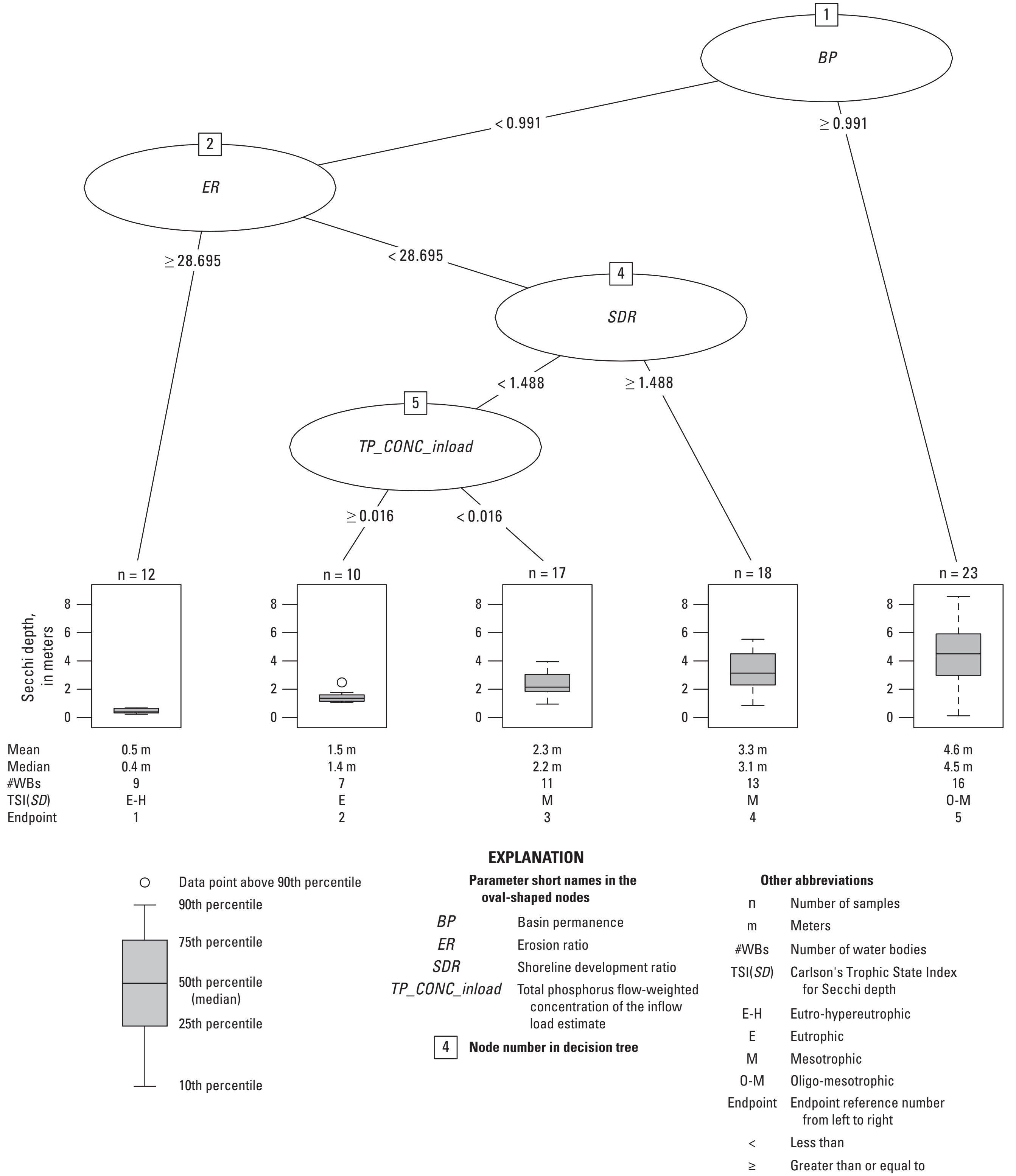


Figure 3. Diagram showing a Secchi depth regression tree for lakes.

Table 2. Lakes identified in the Secchi depth regression tree for endpoint one (eutro-hypereutrophic) in figure 3.

[TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#), number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Basin permanence	Erosion ratio	TSI(*SD*)
Catfish Lake (2)	North Carolina	34.92515821	–77.11213959	0.118	100.154	76.2
Crescent Lake	Florida	29.53292869	–81.55607632	0.468	64.800	66.2
Lake Griffin (2)	Florida	28.86147702	–81.88672892	0.485	29.881	70.7
Lake Kittamagundi (2)	Maryland	39.21207761	–76.85496819	0.062	29.470	74.4
Lake Monroe	Florida	28.83478422	–81.31901778	0.990	33.010	65.7
Lake Seminole	Florida	27.83987302	–82.78127498	0.031	157.490	75.1
Lake Tarpon	Florida	28.07865662	–82.70971972	0.251	46.723	66.2
Lake Thonotosass	Florida	28.06809429	–82.26869452	0.456	30.866	81.2
Trout Lake	Florida	28.86485669	–81.68633538	0.024	172.326	71.5

Table 3. Lakes identified in the Secchi depth regression tree for lakes, endpoint two (eutrophic) in figure 3.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#), number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Shoreline develop-ment ratio	Basin permanence	Erosion ratio	TSI(*SD*)
Beardsley Pond (2)	Connecticut	41.89412460	–73.45042293	0.029	1.482	0.195	16.212	55.2
Brindle Pond	New Hampshire	43.36848020	–71.24997833	0.017	1.288	0.264	19.323	51.8
Crooked Pond	New Hampshire	43.29391100	–71.42464393	0.017	1.352	0.162	18.737	56.4
Lake Kenosia	Connecticut	41.38258187	–73.49805680	0.054	1.446	0.232	17.780	57.4
Laurel Lake (2)	Pennsylvania	41.69210040	–75.12858319	0.031	1.152	0.328	16.470	56.2
Roseland Lake (2)	Connecticut	41.94518347	–71.94881040	0.027	1.371	0.359	16.670	56.2
Yawgoo Pond	Rhode Island	41.50751340	–71.56953240	0.024	1.138	0.352	20.330	46.9

As shown in figure 3, lakes with a basin permanence less than 0.991 and an erosion ratio greater than or equal to 28.695 represent the lakes with the shallowest depths, because they are represented by a low basin permanence and large erosion ratio. The reduced optical clarity is likely inorganic turbidity caused by resuspended bed sediments. Lakes with an erosion ratio less than 28.695, a shoreline development ratio less than 1.488, and a total phosphorus flow-weighted concentration of the inflow load estimate greater than or equal to 0.016, were the next smallest Secchi depth group. These are the more phosphorus-rich lakes, and the reduced optical clarity in these lakes is likely organic turbidity caused by phytoplankton. Those lakes with a shoreline development greater than or equal to 1.488 have greater littoral influence and greater Secchi depths. Lakes with the greatest Secchi depths include those with a basin permanence greater than or equal to 0.991. These are the deeper, V-shaped lakes with less bed sediment exposure to resuspension caused by wind-driven-event mixing and a smaller photic-zone volume to total lake volume ratio than those lakes with less basin permanence.

Table 4. Lakes identified in the Secchi depth regression tree for endpoint three (mesotrophic) in figure 3.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#); number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Shoreline development ratio	Basin permanence	Erosion ratio	TSI(*SD*)
Adder Pond (2)	New Hampshire	43.44724200	–71.80592573	0.0156	1.119	0.234	17.118	56.2
Anawana Lake	New York	41.69691967	–74.67307713	0.0159	1.121	0.420	16.388	41.7
Female Pond	Maine	45.74686393	–69.21582520	0.0098	1.364	0.460	15.903	46.8
Halfmile Pond	Maine	44.84720993	–68.42695427	0.0051	1.292	0.429	15.948	47.0
Hinkley's Pond	Maryland	41.71206047	–70.09442620	0.0045	1.118	0.691	15.888	49.3
Hudson Pond (2)	Maine	46.16757720	–69.01111460	0.0059	1.332	0.617	15.407	54.2
Little Greenough Pond (2)	New Hampshire	44.83856860	–71.13739867	0.0057	1.172	0.272	16.238	50.0
Danforth Ponds (3)	New Hampshire	43.83497300	–71.09561047	0.0081	1.336	0.134	20.662	43.9
Sip Pond (2)	New Hampshire	42.72931720	–72.10023633	0.0127	1.186	0.209	27.320	50.0
Ten Thousand Acre Pond	Maine	45.50817840	–69.94915320	0.0134	1.365	0.124	22.270	50.0
Trafton Pond	Maine	43.84562480	–70.89418520	0.0103	1.285	0.314	16.193	41.9

Table 5. Lakes identified in the Secchi depth regression tree for endpoint four (mesotrophic) in figure 3.

[TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#); number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Shoreline development ratio	Basin permanence	Erosion ratio	TSI(*SD*)
Derby Lake	Vermont	44.94997533	–72.11835893	1.56	0.279	21.056	39.8
Fourth Machias Lake	Maine	45.16874213	–67.97366907	2.86	0.318	25.929	42.9
Halfway Pond	Massachusetts	41.84569047	–70.61749947	1.71	0.632	15.407	44.2
Horseshoe Lake	Maine	44.87017373	–67.57840407	1.60	0.112	20.149	45.0
Little Watchie Pond	Maine	43.77856340	–70.60994827	2.25	0.126	19.472	53.4
Long Pond (4)	New Hampshire	42.68460607	–71.36862320	1.85	0.304	17.761	49.5
Lower Middle Branch Pond (2)	Maine	44.86682033	–68.22573547	1.72	0.578	15.830	51.0
Miles Pond	Vermont	44.44618040	–71.79759793	1.53	0.870	15.621	45.4
Newton Lake	Pennsylvania	41.63743727	–75.55253813	1.80	0.289	17.665	38.8
Peaked Mountain Pond (2)	Maine	44.77770160	–67.70218841	2.24	0.461	15.462	52.4
Tilden Pond	Maine	44.36192613	–69.10414607	1.49	0.450	19.755	41.3
Webster Pond	Maine	45.44285593	–68.18947580	1.59	0.182	17.301	41.1
Wononpakook Lake	Connecticut	41.92932320	–73.45468860	1.55	0.861	15.954	35.8

Table 6. Lakes identified in the Secchi depth regression tree for endpoint five (oligo-mesotrophic) in figure 3.

[TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#); number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Basin permanence	TSI(*SD*)
Duck Lake	Maine	45.13796213	–68.11166580	4.334	34.4
Fourth Debsconeag Lake (2)	Maine	45.75377260	–69.06649160	1.898	34.6
Island Pond (2)	Vermont	44.81305413	–71.88040553	1.568	36.4
Lake Apopka (2)[1]	Florida	28.67289429	–81.67871172	7.818	85.0
Lake Champlain	Vermont	45.01079380	–73.34532973	17.434	43.9
Lake Parker (2)	Vermont	44.72551533	–72.22915933	1.220	42.2
Lake Waramaug (2)	Connecticut	41.68300840	–73.35341680	1.511	42.2
Little Averill Pond	Vermont	44.96326993	–71.70768793	4.451	33.8
Little Big Wood Pond (2)	Maine	45.63096180	–70.33293860	2.594	44.5
Maidstone Lake	Vermont	44.66712320	–71.64996220	3.531	29.1
Norwich Pond	Massachusetts	42.30156307	–72.83456433	1.056	44.4
Cooper Lake	New York	42.06272280	–74.17413553	1.016	37.2
Pleasant Lake (2)	Maine	45.34433240	–67.92492987	3.003	36.2
Skitacook Lake	Maine	46.01997460	–68.06097807	0.992	42.4
Spring Lake	Maine	45.22190013	–68.21820660	1.123	38.3
West Hill Pond	Connecticut	41.89019947	–73.03671040	1.222	31.5

[1]Apparent error in U.S. Environmental Protection Agency National Lake Morphometry Dataset estimate for volume in Lake Apopka (larger volume than reported elsewhere), providing for a much larger calculated basin permanence. The Carlson's Trophic State Index value (85.0) was not used in endpoint five statistics.

Headwater Reservoirs

Of the 117 headwater reservoirs characterized by 158 Secchi depth observations, 39 were classified as eutro-hypereutrophic, 17 eutrophic, and 61 mesotrophic (fig. 4). As with lakes, basin permanence was the heaviest weighted variable, explaining 35 percent of the variability in Secchi depth, followed by relative depth (15 percent), erosion ratio (14 percent), total phosphorus flow-weighted concentration of the inflow load estimate (9 percent), development of volume (9 percent), flushing rate (9 percent), morphometric factor (7 percent), total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow estimate (1 percent) and shoreline development ratio (1 percent). The model-boosting functional gradient descent algorithm separated the recursive partitioning tree into four nodes and five endpoints by using the minimum number of observations in a node considered for splitting, which was set at 50.

Details of the headwater reservoirs identified within each endpoint are included in tables 7–11. The individual Secchi depth or mean Secchi depth (in the case where two or more Secchi depths were recorded) for each lake was converted to Carlson's Secchi depth TSI designation (eq. 7) for validation. In addition, the Secchi depths for each endpoint were averaged and assigned a trophic state (TSI[*SD*], fig. 4).

As shown in figure 4, headwater reservoirs with a relative depth below 0.913 and a basin permanence below 0.047 represent the very shallow, almost filled-in reservoirs, and the reduced optical clarity is likely inorganic turbidity, caused by resuspended bed sediments. Those headwater reservoirs with a relative depth below 0.913, basin permanence greater than or equal to 0.047, and a total nitrogen to total phosphorus flow-weighted concentration of the inflow load estimate less than 22.099 had the next smallest Secchi depth; the reduced optical clarity in these waterbodies is likely organic, caused by phytoplankton. Under these conditions, headwater reservoirs with a total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate of less than 22.099 were more eutro-hypereutrophic than those with total nitrogen to total phosphorus ratio greater than or equal to 22.099. The headwater reservoirs with the greatest Secchi depths include those with a basin permanence greater than or equal to 0.398. These are the deeper V-shaped headwater reservoirs with less bed sediment exposure to resuspension caused by wind-driven event mixing and a smaller photic-zone volume to total reservoir volume ratio than those headwater reservoirs with less basin permanence.

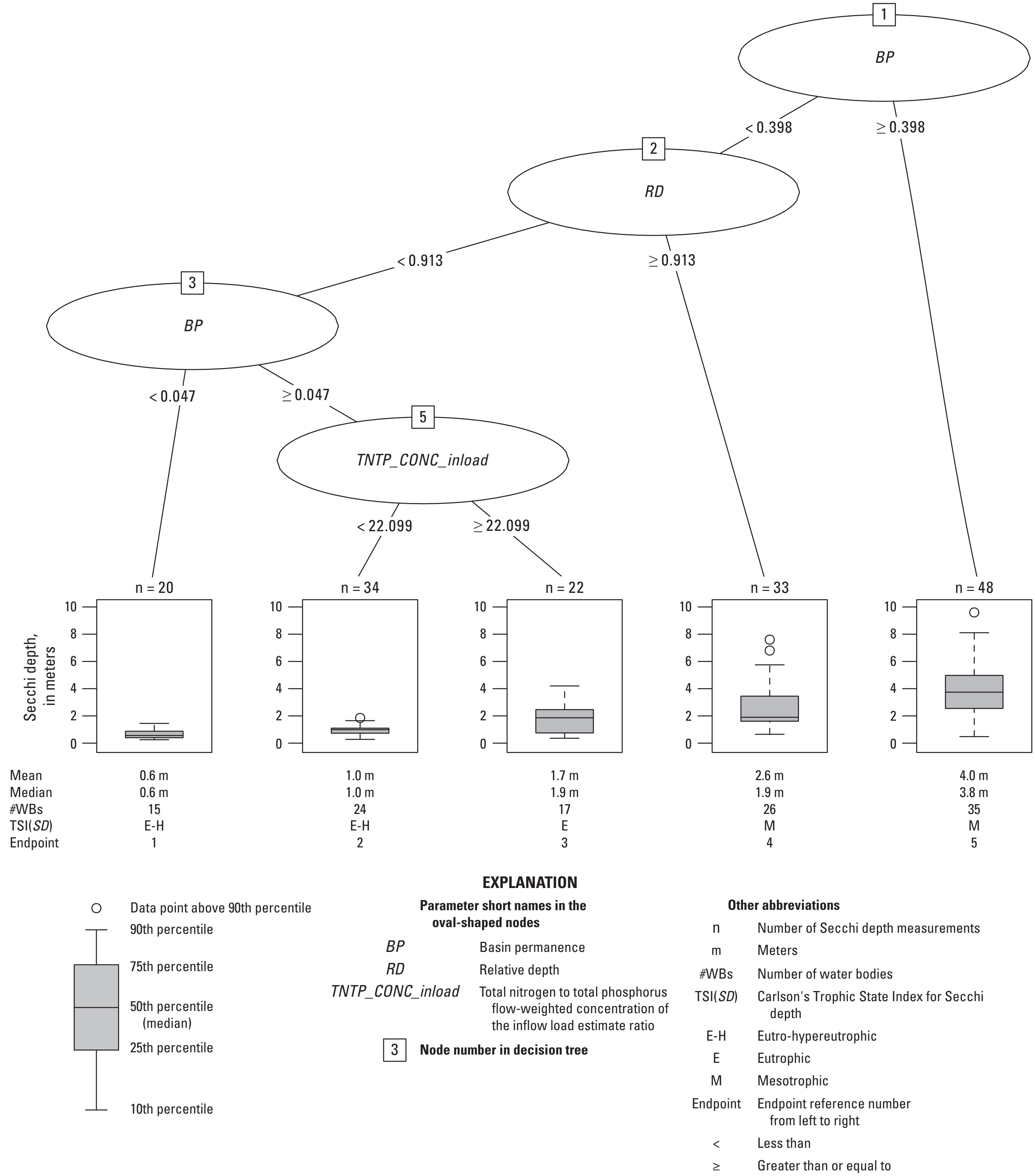


Figure 4. Diagram showing a Secchi depth regression tree for headwater reservoirs.

Table 7. Headwater reservoirs identified in the Secchi depth regression tree for endpoint one (eutro-hypereutrophic) in figure 4.

[TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#); number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Basin permanence	Relative depth	TSI(*SD*)
Cheatham Pond	Virginia	37.29864448	–76.61630552	0.035	0.258	77.8
Crane Pond (3)	South Carolina	33.03726648	–79.98063539	0.010	0.069	70.5
Harrison Lake	Virginia	37.34418641	–77.18614619	0.036	0.248	71.2
Johnsons Pond	Maryland	38.37225367	–75.60249059	0.031	0.129	75.1
Lake Burnt Mills	Virginia	36.84083228	–76.62743512	0.041	0.168	59.3
Lake Greeley	Pennsylvania	41.41542407	–75.01769439	0.037	0.206	61.8
Lees Lake	Alabama	33.88106148	–85.93313531	0.034	0.383	66.2
Maple Lake (2)	New Jersey	39.40601801	–74.77660493	0.036	0.279	63.7
McColley Pond	Delaware	38.96711101	–75.49341399	0.044	0.443	62.0
Red Mill Pond (2)	Delaware	38.75994767	–75.20394119	0.029	0.130	79.4
Reed Bingham Park Lake	Georgia	31.16169062	–83.54321271	0.015	0.019	58.0
Salco Lake	Alabama	30.97246202	–88.05048657	0.025	0.124	54.6
Silver Lake Dover	Delaware	39.16809767	–75.52177213	0.045	0.127	77.8
Trussum Pond	Delaware	38.52521327	–75.51164659	0.019	0.098	68.0
Wrights Pond (2)	Virginia	38.21679141	–77.66322872	0.022	0.252	65.5

Table 8. Headwater reservoirs identified in the Secchi depth regression tree for endpoint two (eutro-hypereutrophic) in figure 4.

[TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#); number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate	Basin permanence	Relative depth	TSI(*SD*)
Bald Run Reservoir	Virginia	38.48914267	–78.00521712	14.427	0.125	0.904	70.0
Beaver Pond (4)	Virginia	37.29686101	–77.88250279	16.027	0.112	0.692	63.4
Belleville Pond (3)	Rhode Island	41.55958607	–71.47316660	21.822	0.164	0.519	59.0
Buckhorn Reservoir	North Carolina	35.69098968	–78.12002372	11.685	0.162	0.162	62.3
Emmit Wood Lake (2)	Alabama	31.61972262	–88.34816071	15.397	0.214	0.733	70.8
Graham-Mebane Lake	North Carolina	36.09513561	–79.33590192	8.984	0.094	0.309	60.3
Lake Fisher	North Carolina	35.48632061	–80.57827712	12.460	0.123	0.387	64.5
Lake Montclair	Virginia	38.61012967	–77.34286219	9.899	0.121	0.781	52.8
Lake Orange	North Carolina	36.14612821	–79.14926332	8.864	0.052	0.319	58.2
Lake Rim	North Carolina	35.03120981	–79.04147679	10.578	0.063	0.544	58.6
Lake Tranquility (3)	New Jersey	40.94915467	–74.78603879	21.378	0.123	0.816	59.9
Little Ocmulgee Lake	Georgia	32.08652362	–82.89547158	15.807	0.111	0.109	62.3
Manassas	Virginia	38.76343741	–77.62268892	13.059	0.265	0.406	54.0
McMath Millpond (2)	Georgia	32.07357908	–84.28822071	9.288	0.074	0.410	60.0
Merle-Smith Lake	Virginia	37.99744987	–78.17659472	11.087	0.088	0.804	58.7
Mossy Lake	Georgia	32.47822382	–83.64390678	14.401	0.213	0.224	59.6
Mott Lake	North Carolina	35.05106561	–79.20661479	8.157	0.084	0.362	49.7
Needwood Lake	Maryland	39.11430787	–77.12951532	17.772	0.235	0.642	64.1
Shelly Lake	North Carolina	35.85653561	–78.66091319	15.581	0.143	0.888	78.6
Swan Lake (2)	Georgia	33.58010528	–84.20447738	7.986	0.053	0.349	60.8
Swimming River Reservoir	New Jersey	40.31904787	–74.11517160	10.829	0.132	0.251	59.3
Union Pond	Connecticut	41.79991587	–72.52818873	14.354	0.132	0.703	54.2
Vaughn Pond	South Carolina	34.32016928	–80.63297352	14.468	0.065	0.586	58.6
Wheeler's Pond	Virginia	37.11828348	–77.62753852	10.919	0.067	0.429	73.2

Table 9. Headwater reservoirs identified in the Secchi depth regression tree for endpoint three (eutrophic) in figure 4.

[TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#); number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate	Basin permanence	Relative depth	TSI(*SD*)
Bowdish Reservoir	Rhode Island	41.92094947	–71.77781893	26.698	0.270	0.569	45.7
Concord Pond	Delaware	38.64255861	–75.55407739	25.447	0.049	0.274	55.4
Coursey Pond	Delaware	38.98123467	–75.52987479	53.061	0.052	0.401	74.7
Diascund Creek Reservoir	Virginia	37.43014121	–76.89440559	27.850	0.150	0.337	66.2
Eagle Lake	Pennsylvania	41.28550140	–75.48624879	34.120	0.229	0.701	51.0
Flat River Reservoir I	Rhode Island	41.70432767	–71.62939853	26.987	0.287	0.788	49.0
Flat River Reservoir II (2)	Rhode Island	41.69451820	–71.59568620	27.680	0.052	0.143	46.5
Jolly Pond (2)	Virginia	37.29717681	–76.81955759	22.623	0.086	0.756	66.4
Lake George	Alabama	34.22274528	–86.83777318	27.243	0.130	0.639	46.1
Little Creek Reservoir (2)	Virginia	37.35023761	–76.84056119	44.697	0.090	0.252	47.0
Loughberry Lake	New York	43.09218160	–73.76790920	38.336	0.099	0.673	44.7
Messerschmidt Pond	Connecticut	41.33835160	–72.48382100	25.720	0.177	0.775	48.3
Mount Hope Lake (2)	New Jersey	40.92464547	–74.53310779	36.398	0.289	0.769	66.1
Piney Run Reservoir	Maryland	39.37679547	–76.89043992	22.376	0.109	0.250	39.3
Ski Lake	Alabama	33.29207748	–87.14681978	22.605	0.187	0.810	48.3
Slack Reservoir	Rhode Island	41.86865667	–71.55384373	40.187	0.165	0.690	55.9
Struble Lake (2)	Pennsylvania	40.10802820	–75.86449679	30.123	0.326	0.594	63.0

Table 10. Headwater reservoirs identified in the Secchi depth regression tree for endpoint four (mesotrophic) in figure 4.

[TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Basin permanence	Relative depth	TSI(*SD*)
Beaver Dam Reservoir	Virginia	37.31324041	–79.81543472	0.127	0.954	40.2
Bissonnette Pond	Connecticut	41.92254887	–72.22045480	0.229	1.620	50.0
Breckinridge Reservoir	Virginia	38.53609741	–77.39147552	0.141	1.093	54.5
Cooper Lake	New York	43.45091833	–73.59341980	0.247	1.688	30.8
Cusky Pond	Massachusetts	42.32378900	–72.09554260	0.170	1.368	62.2
Gorton Pond	Rhode Island	41.70358880	–71.46116500	0.255	1.007	46.1
Holiday Lake	Virginia	37.39143848	–78.63582672	0.308	1.220	43.0
Horton Lake	Pennsylvania	41.71990420	–75.69962773	0.334	2.002	62.3
Kings Mountain #1 Lake (2)	North Carolina	35.20142181	–81.34949852	0.095	1.029	41.9
Lackawanna Lake	Pennsylvania	41.55706880	–75.71780319	0.256	0.978	52.9
Lake Lanier	Virginia	36.65613028	–79.84066112	0.091	0.988	47.1
Lake Lurleen	Alabama	33.28664102	–87.68496351	0.384	1.190	52.8
Lake Nephawin	Pennsylvania	41.63328380	–76.84364572	0.274	1.674	48.0
Lineville Lake (2)	Alabama	33.31912502	–85.80792718	0.138	1.460	52.7
Long Meadow Pond	Connecticut	41.65404800	–73.20985413	0.202	0.922	46.8
Orange Reservoir (2)	New Jersey	40.75908187	–74.28646013	0.222	1.130	65.2
Scituate Reservoir	Rhode Island	41.83357467	–71.59347180	0.328	1.014	58.0
Sequoyah Lake	Georgia	34.54423768	–84.37114038	0.208	1.473	39.9
Slatersville Reservoirs (3)	Rhode Island	41.99438067	–71.59482480	0.299	1.225	49.7
Sly Pond	New York	43.45091833	–73.59341980	0.247	1.688	32.4
Spring Creek Lake (2)	Virginia	37.21370788	–78.61656019	0.254	1.113	52.6
Starlight Lake	Pennsylvania	41.90701620	–75.33349139	0.278	2.147	40.0
Tipton	Pennsylvania	40.67554347	–78.32649772	0.336	1.972	34.8
Tully Lake (2)	Massachusetts	42.64272413	–72.22331540	0.397	1.089	55.0
Wallace Pond	Massachusetts	42.70302060	–71.92482860	0.146	1.220	56.9
Wauregan Reservoir	Connecticut	41.76879020	–71.88754620	0.230	0.926	38.8

Table 11. Headwater reservoirs identified in the Secchi depth regression tree for endpoint five (mesotrophic) in figure 4.

[TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Basin permanence	TSI(*SD*)
Back Lake	New Hampshire	45.08388480	–71.36416200	1.2203	46.5
Beach Pond	Rhode Island	41.58157987	–71.81793373	1.0954	40.4
Beltzville Lake	Pennsylvania	40.85129460	–75.63909473	0.4800	40.4
Blue Ridge Lake (2)	Georgia	34.88245241	–84.28048678	0.5473	43.5
Chain of Ponds	Maine	45.31415460	–70.62642020	0.7760	39.5
Elkhorn Lake	Virginia	38.32728081	–79.22330012	1.3963	39.3
Flying Pond	Maine	44.51498733	–69.99321840	0.4329	39.8
Gantt Reservoir	Alabama	31.40342309	–86.47953398	0.5931	60.3
Halls Pond	Connecticut	41.83728400	–72.11413360	0.4202	41.0
Highland Lake (2)	New Hampshire	43.07887960	–72.09360413	0.3996	44.4
Howard Pond (2)	Maine	44.50598600	–70.71488287	1.1478	39.9
Island Pond	New Hampshire	43.17163793	–72.05954113	0.4909	36.1
J T Budd Pond	Florida	30.38884182	–84.64659258	0.7892	66.2
Lake Allatoona (2)	Georgia	34.16377961	–84.72721171	0.9211	48.6
Lake Habeeb (3)	Maryland	39.70123487	–78.66278399	0.4001	39.4
Lake Marion	South Carolina	33.45532668	–80.16423312	1.2912	60.7
Lake Purdy	Alabama	33.46009342	–86.66825158	0.4366	54.6
Lake Stanmore	Pennsylvania	41.97358100	–75.88156933	0.4512	46.5
Lake Tahoma	North Carolina	35.72289408	–82.07999518	1.1080	43.6
Lewis Smith Reservoir	Alabama	33.94242841	–87.10581998	0.4724	38.4
Pleasant Lake (2)	Maine	44.00951813	–70.52283867	3.1160	33.6
Raystown Lake (2)	Pennsylvania	40.43355054	–78.00711259	2.4654	48.6
Riga Lake	Connecticut	42.01791447	–73.47768820	0.5649	27.4
Roderique Pond	Maine	45.66012560	–69.81335627	2.6168	40.3
Round Valley Reservoir	New Jersey	40.61086507	–74.84524579	13.7681	46.8
Savage River Reservoir	Maryland	39.50767201	–79.13409419	1.1789	32.2
Sebasticook Lake (2)	Maine	44.83557700	–69.27198280	2.5206	47.3
Spoonwood Pond	New Hampshire	42.99408540	–72.06537920	1.2710	30.7
Table Rock Reservoir (3)	South Carolina	35.06469841	–82.67160492	1.7039	36.3
Turners Pond	Pennsylvania	41.97358100	–75.88156933	0.4512	46.2
Walker Lake	Pennsylvania	40.79669247	–77.19614699	0.5581	68.6
Weiss Reservoir	Alabama	34.13262221	–85.79426658	1.0874	70.6
West Hill Pond	Connecticut	41.89019947	–73.03671040	1.2216	32.3
Willard Pond (2)	New Hampshire	43.01833240	–72.01866020	1.0140	30.7
Winnisquam Lake (2)	New Hampshire	43.48068553	–71.53552060	3.7105	33.1

Downstream Reservoirs

Of the 47 downstream reservoirs characterized by 59 Secchi depth observations, 13 were classified as eutro-hypereutrophic, 18 eutrophic, 11 mesotrophic, and 5 oligo-mesotrophic (fig. 5). Total phosphorus flow-weighted concentration of the inflow load estimate was the highest weighted variable (25 percent), followed by the total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate (17 percent), total nitrogen flow-weighted concentration of the inflow load estimate (16 percent), morphometric factor (11 percent), relative depth (11 percent), erosion ratio (7 percent), basin permanence (7 percent), flushing rate (4 percent), shoreline development ratio (2 percent), and development of volume (1 percent). The model boosting functional gradient descent algorithm separated the recursive partitioning tree into four nodes and five endpoints by using the minimum number of observations in a node considered for splitting, which was set at 18.

Details of the downstream reservoirs identified within each endpoint are included in tables 12–16. The individual Secchi depth or mean Secchi depth (in the case where two or more Secchi depths were recorded) for each lake was converted to Carlson's Secchi depth trophic state value (eq. 7) for validation. In addition, the Secchi depths for each endpoint were averaged and assigned a trophic state (TSI[*SD*], fig. 5).

As shown in figure 5, downstream reservoirs with a total phosphorus flow-weighted concentration of the inflow load estimate greater than or equal to 0.031 mg/L represent the nutrient rich, eutrophic and eutro-hypereutrophic downstream reservoirs. Those with an erosion ratio greater than or equal to 17.071 and a total nitrogen flow-weighted concentration of the inflow load estimate greater than or equal to 0.794 mg/L had the smallest Secchi depths, collectively. Those with an erosion ratio greater than or equal to 17.071 and a total nitrogen flow-weighted concentration of the inflow load estimate less than 0.794 mg/L represent reservoirs with the lowest total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate (less than 25.6:1), the second highest weighted variable, not visually expressed in the regression tree. The group with the greatest Secchi depths includes those downstream reservoirs with a total phosphorus flow-weighted concentration of the inflow load estimate less than 0.031 mg/L and total nitrogen flow-weighted concentration of the inflow load estimate greater than or equal to 0.71 mg/L. These are the most oligo-mesotrophic downstream reservoirs with the highest total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate (greater than or equal to 22.9:1).

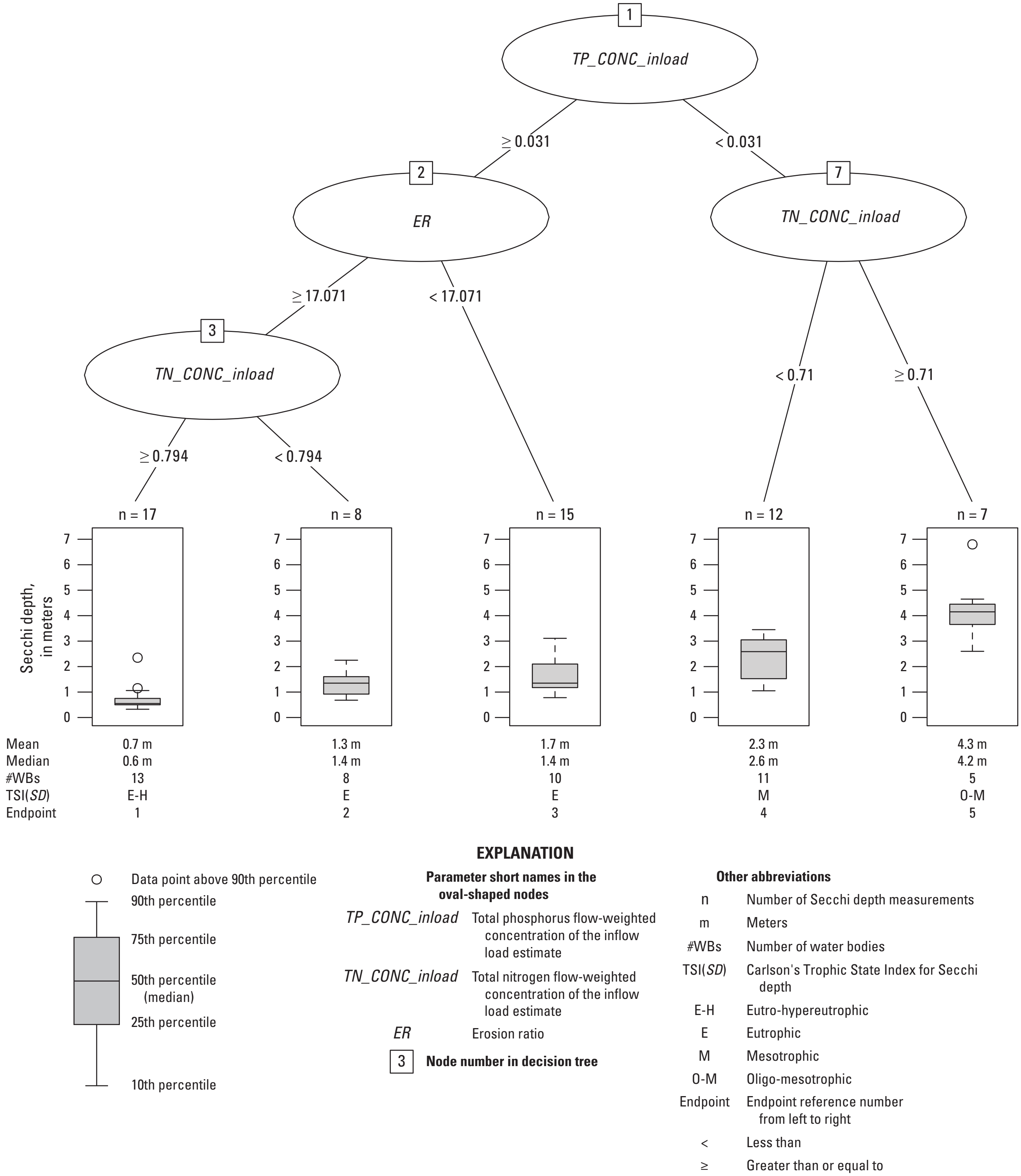


Figure 5. Diagram showing a Secchi depth regression tree for downstream reservoirs.

Table 12. Downstream reservoirs identified in the Secchi depth regression tree for endpoint one (eutro-hypereutrophic) in figure 5.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Erosion ratio	TSI(*SD*)
Beaverdam Lake	North Carolina	35.81493621	–78.53290072	1.099	0.073	24.027	67.4
City Lake	North Carolina	34.88294508	–79.69233539	0.879	0.061	33.006	64.5
Concord Pond	Delaware	38.64255861	–75.55407739	3.226	0.127	42.911	59.2
Coursey Pond	Delaware	38.98879441	–75.51097759	3.318	0.060	31.465	55.3
Lake Brandt	North Carolina	36.17273048	–79.83855119	1.400	0.102	18.966	66.7
Lake Demopolis (2)	Alabama	32.52054008	–87.87913091	1.066	0.122	126.623	68.9
Lake Lee (2)	North Carolina	34.96593248	–80.51090979	2.617	0.193	28.723	72.6
Lake Monroe	Florida	28.83478422	–81.31901778	0.796	0.082	33.010	67.8
Lake Townsend	North Carolina	36.18933701	–79.73196512	1.115	0.058	17.675	58.0
Logan Martin Lake	Alabama	33.42597982	–86.33653698	0.858	0.079	17.257	63.7
Noxontown Pond (3)	Delaware	39.43391441	–75.68356033	2.278	0.116	22.887	71.7
Packanack Lake	New Jersey	40.93390807	–74.25638673	2.071	0.085	24.337	68.6
Southern Pines Waterworks	North Carolina	35.21528021	–79.40105612	1.479	0.100	24.131	47.7

Table 13. Downstream reservoirs identified in the Secchi depth regression tree for endpoint two (eutrophic) in figure 5.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Erosion ratio	TSI(*SD*)
Coneross Creek Reservoir	South Carolina	34.72319988	–83.10458858	0.474	0.031	20.9	54.6
Hennington Lake	Mississippi	31.29583249	–89.44115077	0.791	0.070	22.3	55.7
Jordan Lake	Alabama	32.61890522	–86.25686358	0.751	0.063	20.7	51.9
Lay Reservoir	Alabama	32.61890522	–86.25686358	0.751	0.063	20.7	51.9
Mirror Lake	New Jersey	39.96822581	–74.57956959	0.578	0.033	47.9	62.3
Mott Lake	North Carolina	35.05106561	–79.20661479	0.472	0.058	31.5	49.7
R E 'Bob' Woodruff Reservoir	Alabama	32.32431628	–86.78413758	0.719	0.066	20.7	60.1
South Pacolet River Reservoir Number One	South Carolina	35.11106008	–81.96997492	0.499	0.031	28.2	60.1

Table 14. Downstream reservoirs identified in the Secchi depth regression tree for endpoint three (eutrophic) in figure 5.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Erosion ratio	TSI(*SD*)
Falls Lake	North Carolina	35.94103148	–78.58072879	0.126	16.011	63.6
Holt Lake (3)	Alabama	33.25401442	–87.44933797	0.074	15.954	52.2
Lake Hickory (3)	North Carolina	35.82214701	–81.19285118	0.079	15.825	51.9
Lake Wylie	North Carolina	35.02035681	–81.00767752	0.065	16.886	50.2
Nickajack Lake	Tennessee	35.00009628	–85.69731378	0.049	16.648	50.8
Philpott Reservoir	Virginia	36.78138081	–80.02773832	0.059	15.811	43.7
Pickwick Lake	Tennessee	34.79591921	–87.62492884	0.073	16.143	58.0
Rhodhiss (2)	North Carolina	35.77338108	–81.43794752	0.079	15.426	57.2
Sconti Lake	Georgia	34.45104308	–84.28569278	0.038	16.124	48.6
Tuckertown Reservoir	North Carolina	35.48482108	–80.17678299	0.135	16.675	59.6

Table 15. Downstream reservoirs identified in the Secchi depth regression tree for endpoint four (mesotrophic) in figure 5.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	TSI(*SD*)
Besse Bog Reservoir	Massachusetts	41.80847460	–70.64241760	0.006	0.287	43.0
Keech Pond	Rhode Island	41.90201800	–71.67669093	0.019	0.584	58.0
Lake Stockwell-19	New Jersey	39.86291721	–74.80363219	0.016	0.566	59.3
Little Lake	Maine	44.78414740	–67.19145667	0.005	0.184	45.0
Long Pond	Maine	45.31415460	–70.62642020	0.013	0.379	42.9
Middle Chain Pond	Maine	45.22046073	–68.07062400	0.004	0.126	49.6
Pocono Lake	Pennsylvania	41.09597780	–75.54254893	0.013	0.639	53.4
Second Buttermilk Pond	Maine	45.32849713	–69.26694807	0.007	0.153	46.1
Smith and Sayles Reservoir	Rhode Island	41.90201800	–71.67669093	0.019	0.584	46.5
Spaulding Pond	New Hampshire	43.37836353	–70.98390127	0.014	0.330	44.9
Waller Mill Reservoir (2)	Virginia	37.30301428	–76.70195132	0.017	0.447	48.3

Table 16. Downstream reservoirs identified in the Secchi depth regression tree for endpoint five (oligo-mesotrophic) in figure 6.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	TSI(*SD*)
Lake Altoona	Pennsylvania	40.49296647	–78.45661759	0.782	0.016	32.4
Beltzville Dam	Pennsylvania	40.85129460	–75.63909473	0.889	0.022	39.9
Groton Reservoir	Connecticut	41.35043667	–72.03650873	0.781	0.019	39.1
Pachaug Pond	Connecticut	41.58226140	–71.92998840	0.955	0.027	46.2
Morris Reservoir (3)	Connecticut	41.67475140	–73.14349713	0.849	[1]0.0305	40.2

[1]Four-digit decimal number used in the partition tree analysis.

Chlorophyll *a*

Lakes

Of the 64 lakes characterized by 91 chlorophyll *a* sample concentrations, 16 were classified as oligo-mesotrophic, 27 mesotrophic, 12 eutrophic, and 9 hypereutrophic (fig. 6). Total phosphorus flow-weighted concentration of the inflow load estimate explained 25 percent of the variability in log10 chlorophyll *a* concentrations, followed by the total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate (16 percent), total nitrogen flow-weighted concentration of the inflow load estimate (14 percent), relative depth (13 percent), basin permanence (12 percent), morphometric factor (12 percent), flushing rate (5 percent), development of volume (1 percent), and shoreline development ratio (1 percent). The model-boosting functional gradient descent algorithm separated the recursive partitioning tree into four nodes and five endpoints by using the minimum number of observations in a node considered for splitting, which was set at 40.

Details of the lakes identified within each endpoint are included in tables 17–21. The individual chlorophyll *a* concentration or mean chlorophyll *a* concentration (in the case where two or more chlorophyll *a* concentrations were recorded) for each lake was converted to the TSI value for chlorophyll *a* (eq. 8) for validation. In addition, the chlorophyll *a* concentrations for each endpoint were averaged and assigned a TSI designation (fig. 6).

As shown in figure 6, lakes with a total phosphorus flow-weighted concentration of the inflow load estimate less than 0.081 mg/L and a flushing rate less than 1.463 had the lowest chlorophyll *a* concentrations. These lakes had a relatively low flushing rate compared to the other lakes with a total phosphorus flow-weighted concentrations of the inflow load estimate less than 0.081 mg/L. Development of volume played a role for lakes with a flushing rate greater than or equal to 1.463 and a total phosphorus flow-weighted concentration of the inflow load estimate less than 0.025 mg/L. The deeper lakes generally having a V-shaped profile and lower development of volume (less than 1.216), were lower in chlorophyll *a* concentration than the shallower lakes generally having a flat-bottom profile and higher development of volume (greater than or equal to 1.216). The latter may have higher internal phosphorus loading (mixis), resulting in higher chlorophyll *a* concentrations. Chlorophyll *a* concentrations were higher in lakes with a flushing rate greater than or equal to 1.463 and a total phosphorus flow-weighted concentration of the inflow load of less than 0.081 mg/L and greater than or equal to 0.025 mg/L. The lakes with the highest chlorophyll *a* concentrations were those with a total phosphorus flow-weighted concentration of the inflow load estimate greater than or equal to 0.081 mg/L.

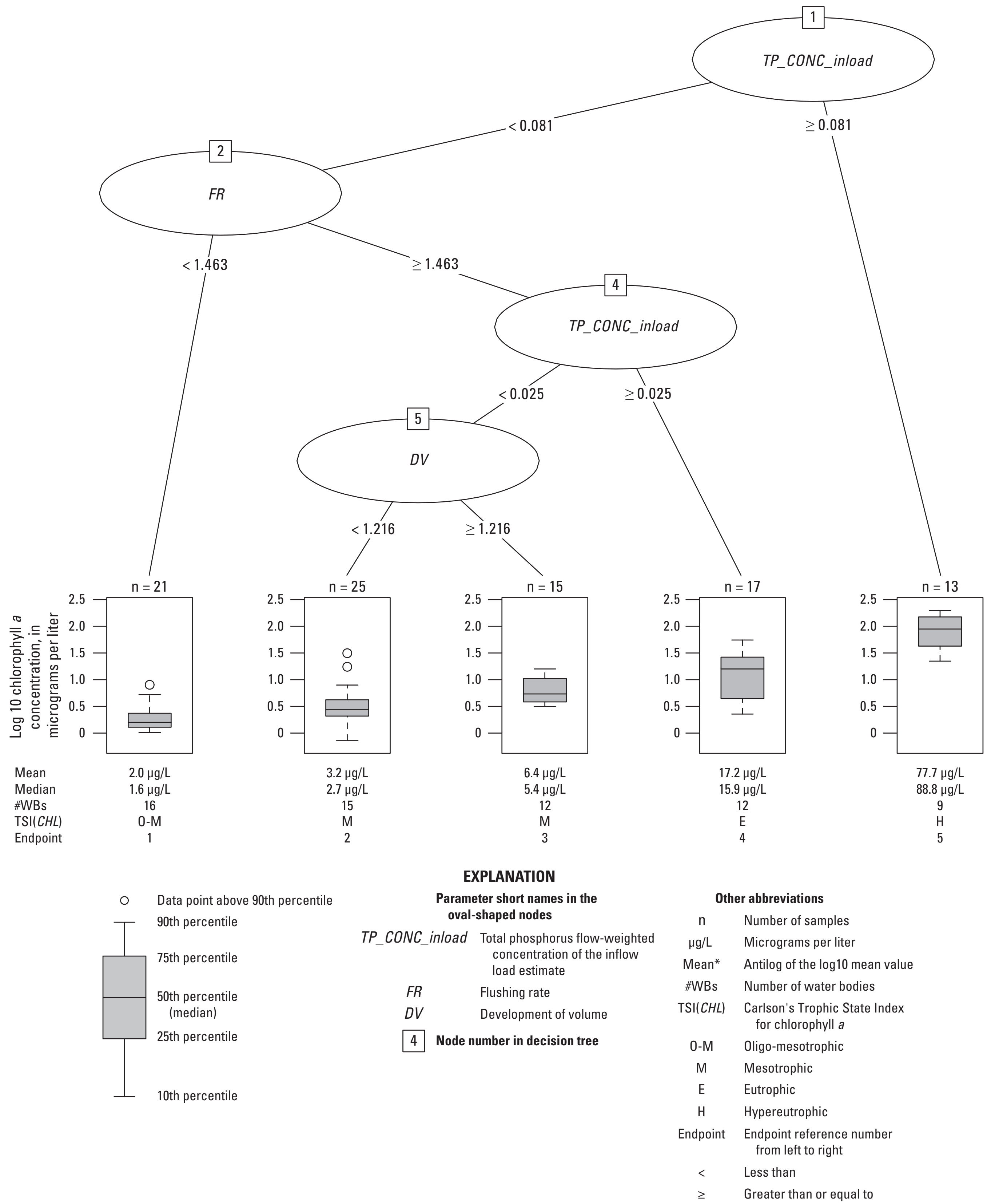


Figure 6. Diagram showing a chlorophyll *a* regression tree for lakes.

Table 17. Lakes identified in the chlorophyll *a* regression tree for endpoint one (oligo-mesotrophic) in figure 6.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Flushing rate	TSI(*CHL*)
Cooper Lake	New York	42.06272280	–74.17413553	0.023	0.221	33.8
Duck Lake	Maine	45.13796213	–68.11166580	0.007	0.197	30.9
Fourth Debsconeag Lake (2)	Maine	45.75377260	–69.06649160	0.008	1.159	32.6
Island Pond (2)	Vermont	44.81305413	–71.88040553	0.021	1.318	41.4
Lake Champlain	Vermont	45.01079380	–73.34532973	0.057	0.589	42.6
Lake Waramaug (2)	Connecticut	41.68300840	–73.35341680	0.031	1.043	49.0
Little Averill Pond	Vermont	44.96326993	–71.70768793	0.028	0.303	36.6
Maidstone Lake	Vermont	44.66712320	–71.64996220	0.011	0.249	30.8
Newton Lake	Pennsylvania	41.63743727	–75.55253813	0.065	0.925	39.0
Norwich Pond	Massachusetts	42.30156307	–72.83456433	0.021	0.405	46.5
Peaked Mountain Pond (2)	Maine	44.77770160	–67.70218841	0.006	0.715	33.9
Plainfield Pond	Massachusetts	42.54642100	–72.95535300	0.020	1.104	30.8
Pleasant Lake (2)	Maine	45.34433240	–67.92492987	0.007	0.650	36.4
Riga Lake	New York	42.01791447	–73.47768820	0.026	1.446	33.0
Spring Lake	Maine	45.22190013	–68.21820660	0.006	0.437	35.6
West Hill Pond	Connecticut	41.89019947	–73.03671040	0.027	0.305	35.1

Table 18. Lakes identified in the chlorophyll *a* regression tree for endpoint two (mesotrophic) in figure 6.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Development of volume	Flushing rate	TSI(*CHL*)
Anawana Lake	New York	41.69691967	–74.67307713	0.016	1.192	2.805	36.7
Brindle Pond	New Hampshire	43.36848020	–71.24997833	0.017	1.145	24.024	42.5
Catfish Lake (2)	North Carolina	34.92515821	–77.11213959	1.41×10^{-6}	1.070	2.608	54.5
Dan Forth Ponds (3)	New Hampshire	43.83497300	–71.09561047	0.008	[1]1.2155	152.195	38.2
Fourth Machias Lake	Maine	45.16874213	–67.97366907	0.005	0.870	15.590	36.6
Halfway Pond	Massachusetts	41.84569047	–70.61749947	0.004	1.173	3.098	64.4
Little Big Wood Pond (2)	Maine	45.63096180	–70.33293860	0.012	1.003	2.702	39.8
Little Watchie Pond	Maine	43.77856340	–70.60994827	0.004	1.147	5.844	46.1
Long Pond	New York	44.34754793	–74.40093260	0.013	0.972	3.043	42.2
Lower Middle Branch Pond (3)	Maine	44.86682033	–68.22573547	0.003	1.044	5.224	39.2
Miles Pond (3)	Vermont	44.44618040	–71.79759793	0.021	1.125	2.397	31.8
Sip Pond (2)	New Hampshire	42.72931720	–72.10023633	0.013	1.178	11.087	41.8
Skitacook Lake	Maine	46.01997460	–68.06097807	0.011	1.020	2.095	38.6
Tilden Pond (2)	Maine	44.36192613	–69.10414607	0.014	1.042	5.796	45.8
Tomhegan Pond	Maine	45.78368973	–69.89469527	0.008	0.856	5.647	50.9

[1]Four-digit decimal number used in the partition tree analysis.

Table 19. Lakes identified in the chlorophyll *a* regression tree for endpoint three (mesotrophic) in figure 6.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Development of volume	Flushing rate	TSI(*CHL*)
Adder Pond (2)	New Hampshire	43.44724200	–71.80592573	0.016	1.318	1.499	48.7
Crooked Pond	New Hampshire	43.29391100	–71.42464393	0.017	1.407	1.577	56.6
Female Pond	Maine	45.74686393	–69.21582520	0.010	1.316	18.351	45.0
Halfmile Pond	Maine	44.84720993	–68.42695427	0.005	1.370	2.298	41.9
Hinkley's Pond	Massachusetts	41.71206047	–70.09442620	0.005	1.250	6.319	53.8
Hudson Pond (2)	Maine	46.16757720	–69.01111460	0.006	1.217	2.389	52.2
Little Greenough Pond (2)	New Hampshire	44.83856860	–71.13739867	0.006	1.310	9.683	45.3
Long Pond	Massachusetts	41.65468280	–70.33527527	0.006	1.374	46.487	53.6
Ten Thousand Acre Pond	Maine	45.50817840	–69.94915320	0.013	1.365	10.912	42.8
Trafton Pond	Maine	43.84562480	–70.89418520	0.010	1.251	7.965	57.7
Webster Pond	Maine	45.44285593	–68.18947580	0.009	1.359	3.609	44.0
Yawgoo Pond	Rhode Island	41.50751340	–71.56953240	0.024	1.228	3.241	43.6

Table 20. Lakes identified in the chlorophyll *a* regression tree for endpoint four (eutrophic) in figure 6.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Flushing rate	TSI(*CHL*)
Beardsley Pond (2)	Connecticut	41.89412460	–73.45042293	0.029	1.664	50.6
Chapman Pond	Rhode Island	41.38390040	–71.79087740	0.033	1.481	45.2
Crescent Lake	Florida	29.53292869	–81.55607632	0.062	16.143	70.0
Derby Lake	Vermont	44.94997533	–72.11835893	0.045	2.183	38.9
Lake Kenosia	Connecticut	41.38258187	–73.49805680	0.054	6.111	60.9
Lake Parker (2)	Vermont	44.72551533	–72.22915933	0.040	2.678	44.7
Laurel Lake (2)	Pennsylvania	41.69210040	–75.12858319	0.031	2.217	61.8
Long Pond (2)	New Hampshire	42.68460607	–71.36862320	0.031	1.520	56.5
Roseland Lake (2)	Connecticut	41.94518347	–71.94881040	0.027	45.964	63.1
Shippee Pond	Vermont	42.74777127	–72.83323640	0.035	2.984	50.7
White Lake	Florida	30.31497822	–82.87553392	0.080	2.981	57.7
Wononpakook Lake	Connecticut	41.92932320	–73.45468860	0.028	1.760	44.6

Table 21. Lakes identified in the chlorophyll *a* regression tree for endpoint five (hypereutrophic) in figure 6.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	TSI(*CHL*)
Lake Apopka (2)	Florida	28.67289429	–81.67871172	0.230	76.7
Lake Griffin (2)	Florida	28.86147702	–81.88672892	0.108	77.7
Lake Kittamagundi (2)	Maryland	39.21207761	–76.85496819	0.137	67.4
Lake Monroe	Florida	28.83478422	–81.31901778	0.082	64.2
Lake Seminole	Florida	27.83987302	–82.78127498	0.322	76.2
Lake Tarpon	Florida	28.07865662	–82.70971972	0.117	66.5
Lake Thonotosass	Florida	28.06809429	–82.26869452	0.253	82.0
Leonard Pond (2)	Maryland	38.42298901	–75.56371879	0.118	64.3
Trout Lake	Florida	28.86485669	–81.68633538	0.156	75.6

Headwater Reservoirs

Of the 122 headwater reservoirs characterized by 164 chlorophyll *a* sample concentrations, 31 were classified as mesotrophic, 16 meso-eutrophic, 54 eutrophic, and 20 eutro-hypereutrophic (fig. 7). Total phosphorus flow-weighted concentration of the inflow load estimate explained 28 percent of the variability in log10 chlorophyll *a* concentrations, followed by the total nitrogen flow-weighted concentration of the inflow load estimate (21 percent), basin permanence (15 percent), relative depth (7 percent), flushing rate (7 percent), erosion ratio (6 percent), total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate (6 percent), morphometric factor (4 percent), shoreline development ratio (4 percent), and development of volume (1 percent). The model-boosting functional gradient descent algorithm separated the recursive partitioning tree into four nodes and five endpoints by using the minimum number of observations in a node considered for splitting, which was set at 50.

Details of the headwater reservoirs identified within each endpoint are included in tables 22–26. The individual chlorophyll *a* concentration or mean chlorophyll *a* concentration (in the case where two or more chlorophyll *a* concentrations were recorded) for each reservoir was converted to Carlson’s chlorophyll *a* trophic state value (eq. 8) for validation. In addition, the chlorophyll *a* concentrations for each endpoint were averaged and assigned a trophic state (TSI[*CHL*], fig. 7).

As shown in figure 7, headwater reservoirs with a total phosphorus flow-weighted concentration of the inflow load estimate less than 0.062 mg/L and a basin permanence greater than or equal to 0.335 had the lowest chlorophyll *a* concentrations. The morphometric factor had an influence on those headwater reservoirs with a total phosphorus flow-weighted concentration of the inflow load estimate less than 0.062 mg/L and basin permanence less than 0.335. Internal phosphorus loading (mixis) may play a role in those with a morphometric factor less than 4.7, resulting in higher chlorophyll *a* concentrations. Chlorophyll *a* concentrations were also high in headwater reservoirs with a flow-weighted total phosphorus flow-weighted concentration of the inflow load estimate greater than or equal to 0.062 mg/L, the highest being for those headwater reservoirs with a total nitrogen flow-weighted concentration of the inflow load estimate greater than or equal to 1.903 mg/L.

It is interesting that endpoints 3 and 4 are somewhat similar in data distribution and trophic state. Internal phosphorus loading may likely be the dominant phosphorus source in headwater reservoirs within endpoint 3 during the thermal stratification season, whereas external phosphorus loading is likely the dominant source for those within endpoint 4. Nutrient management strategies for these two headwater reservoir groups would likely differ because the dominant sources of phosphorus differ. A watershed total maximum daily load applied to waterbodies in endpoint 3 will likely not be as effective as one applied to waterbodies in endpoint 4. Mitigation of internal sources of phosphorus for headwater reservoirs within endpoint 3 would likely be more effective.

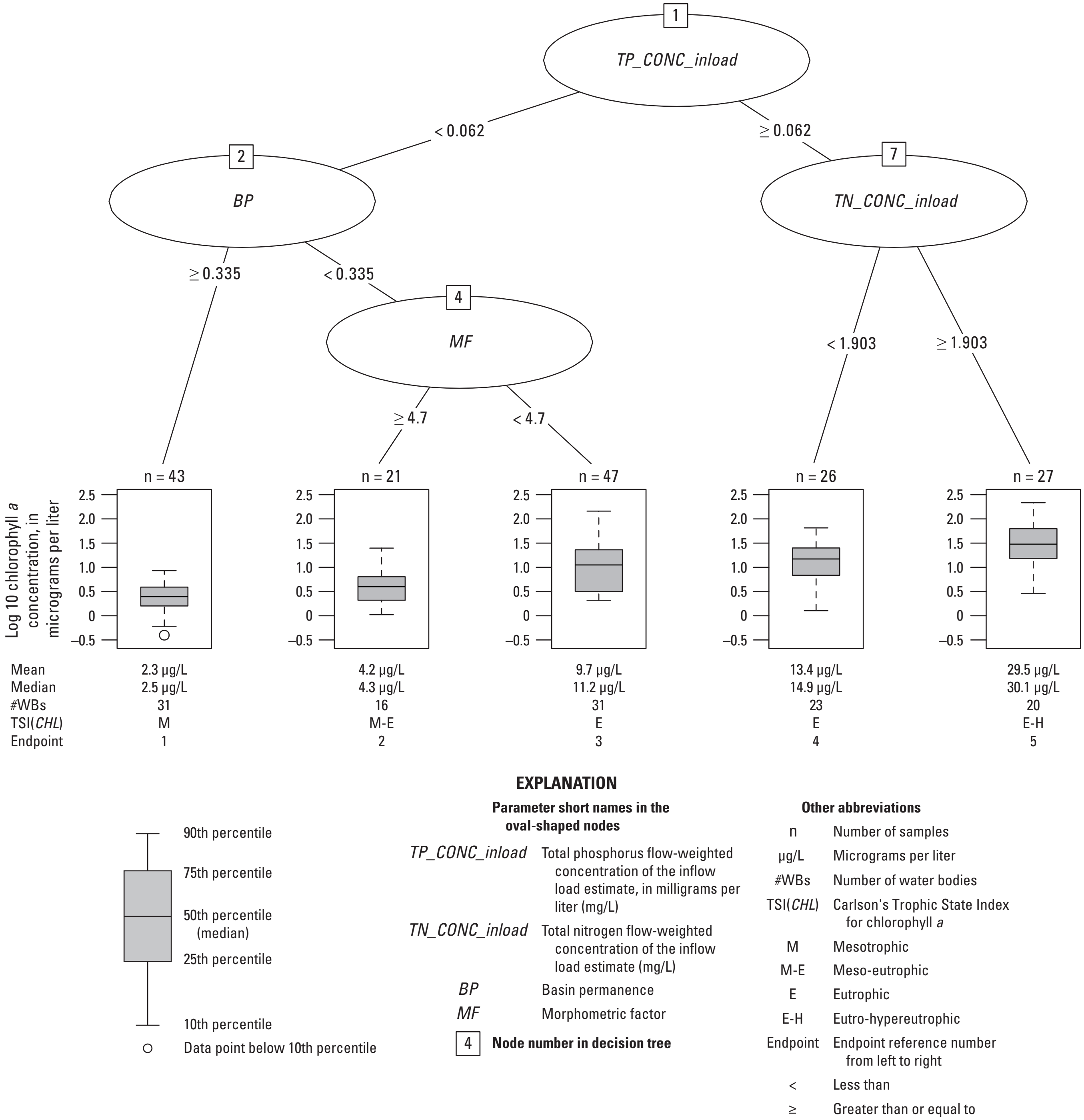


Figure 7. Diagram showing a chlorophyll *a* regression tree for headwater reservoirs.

Table 22. Headwater reservoirs identified in the chlorophyll *a* regression tree for endpoint one (mesotrophic) in figure 7.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Basin permanence	TSI(*CHL*)
Back Lake	New Hampshire	45.08388480	–71.36416200	0.017	1.220	41.3
Beach Pond	Rhode Island	41.58157987	–71.81793373	0.012	1.095	40.6
Beltzville Lake	Pennsylvania	40.85129460	–75.63909473	0.022	0.480	46.2
Blue Ridge Lake (2)	Georgia	34.88245241	–84.28048678	0.027	0.547	34.3
Chain of Ponds	Maine	45.31415460	–70.62642020	0.013	0.776	41.5
Elkhorn Lake	Virginia	38.32728081	–79.22330012	0.011	1.396	39.5
Flying Pond	Maine	44.51498733	–69.99321840	0.009	0.433	37.0
Halls Pond	Connecticut	41.83728400	–72.11413360	0.022	0.420	40.8
Highland Lake (2)	New Hampshire	43.07887960	–72.09360413	0.025	0.400	43.8
Howard Pond (2)	Maine	44.50598600	–70.71488287	0.012	1.148	38.9
Island Pond	New Hampshire	43.17163793	–72.05954113	0.024	0.491	35.8
Lake Habeeb (3)	Maryland	39.70123487	–78.66278399	0.052	0.400	37.3
Lake Lurleen	Alabama	33.28664102	–87.68496351	0.016	0.384	48.3
Lake Stanmore	Pennsylvania	41.97358100	–75.88156933	0.024	0.451	51.7
Lake Tahoma	North Carolina	35.72289408	–82.07999518	0.031	1.108	37.6
Lewis Smith Reservoir	Alabama	33.94242841	–87.10581998	0.052	0.472	28.1
Pleasant Lake (2)	Maine	44.00951813	–70.52283867	0.011	3.116	37.0
Raystown Lake (3)	Pennsylvania	40.43355054	–78.00711259	0.060	2.465	44.4
Riga Lake	Connecticut	42.01791447	–73.47768820	0.026	0.565	30.0
Roderique Pond	Maine	45.66012560	–69.81335627	0.009	2.617	42.0
Round Valley Reservoir	New Jersey	40.61086507	–74.84524579	0.020	13.768	46.5
Savage River Reservoir	Maryland	39.50767201	–79.13409419	0.033	1.179	35.7
Sebasticook Lake (2)	Maine	44.83557700	–69.27198280	0.029	2.521	50.2
Spoonwood Pond	New Hampshire	42.99408540	–72.06537920	0.017	1.271	25.8
Stump Pond	Rhode Island	41.69995907	–71.63711620	0.012	0.436	41.2
Table Rock Reservoir	South Carolina	35.06469841	–82.67160492	0.005	1.704	33.2
Tipton	Pennsylvania	40.67554347	–78.32649772	0.009	0.336	42.0
Tully Lake (2)	Massachusetts	42.64272413	–72.22331540	0.020	0.397	49.8
West Hill Pond	Connecticut	41.89019947	–73.03671040	0.027	1.222	34.9
Willard Pond (2)	New Hampshire	43.01833240	–72.01866020	0.024	1.014	26.9
Winnisquam Lake (2)	New Hampshire	43.48068553	–71.53552060	0.005	3.711	34.6

Table 23. Headwater reservoirs identified in the chlorophyll *a* regression tree for endpoint two (meso-eutrophic) in figure 7.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Morpho-metric factor	Basin perma-nence	TSI(*CHL*)
Bissonnette Pond	Connecticut	41.92254887	–72.22045480	0.030	7.6	0.229	53.6
Breckinridge Reservoir	Virginia	38.53609741	–77.39147552	0.023	5.9	0.141	48.8
Cooper Lake	New York	43.45091833	–73.59341980	0.020	8.0	0.247	31.1
Cusky Pond	Massachusetts	42.32378900	–72.09554260	0.038	6.7	0.170	41.7
Haynes Reservoir	Massachusetts	42.54266987	–71.81759893	0.017	6.4	0.271	48.1
Holiday Lake	Virginia	37.39143848	–78.63582672	0.055	5.8	0.308	58.3
Horton Lake	Pennsylvania	41.71990420	–75.69962773	0.044	10.0	0.334	37.8
Kings Mountain #1 Lake (2)	North Carolina	35.20142181	–81.34949852	0.035	4.8	0.095	44.1
Lineville Lake (2)	Alabama	33.31912502	–85.80792718	0.048	6.2	0.138	62.1
Sequoyah Lake	Georgia	34.54423768	–84.37114038	0.043	7.7	0.208	33.2
Slatersville Reservoirs (3)	Rhode Island	41.99438067	–71.59482480	0.030	6.1	0.299	36.5
Sly Pond	New York	43.45091833	–73.59341980	0.020	8.0	0.247	33.5
Spring Creek Lake (2)	Virginia	37.21370788	–78.61656019	0.056	5.2	0.254	45.6
Starlight Lake	Pennsylvania	41.90701620	–75.33349139	0.047	11.5	0.278	45.9
Wallace Pond	Massachusetts	42.70302060	–71.92482860	0.020	6.1	0.146	41.6
Wauregan Reservoir	Connecticut	41.76879020	–71.88754620	0.031	5.2	0.230	33.5

Table 24. Headwater reservoirs identified in the chlorophyll *a* regression tree for endpoint three (eutrophic) in figure 7.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Morpho-metric factor	Basin perma-nence	TSI(*CHL*)
Belleville Pond (3)	Rhode Island	41.559586070	–71.473166600	0.034	2.0	0.164	52.0
Bowdish Reservoir	Rhode Island	41.920949470	–71.777818930	0.017	2.6	0.270	39.8
Cheatham Pond	Virginia	37.298644480	–76.616305520	0.018	1.1	0.035	72.3
Crane Pond (3)	South Carolina	33.037266480	–79.980635390	0.038	0.3	0.010	56.7
Diascund Creek Reservoir	Virginia	37.430141210	–76.894405590	0.022	1.0	0.150	63.1
Eagle Lake	Pennsylvania	41.285501400	–75.486248790	0.050	3.5	0.229	46.8
Emmit Wood Lake (2)	Alabama	31.619722620	–88.348160710	0.024	3.4	0.214	72.5
Flat River Reservoir (3)	Rhode Island	41.694518200	–71.595686200	0.016	0.5	0.052	38.9
Harrison Lake	Virginia	37.344186410	–77.186146190	0.043	1.0	0.036	55.1
Jolly Pond (2)	Virginia	37.297176810	–76.819557590	0.020	4.1	0.086	66.7
Lackawanna Lake	Pennsylvania	41.557068800	–75.717803190	0.045	3.9	0.256	62.5
Lake Greeley	Pennsylvania	41.415424070	–75.017694390	0.031	1.0	0.037	54.7
Lake Jean	Pennsylvania	41.335298800	–76.299781130	0.016	1.9	0.219	54.3
Lake Naomi	Pennsylvania	41.108639270	–75.473184330	0.016	1.7	0.190	41.8
Lake Rim	North Carolina	35.031209810	–79.041476790	0.059	2.6	0.063	58.2
Lake Tranquility (3)	New Jersey	40.949154670	–74.786038790	0.038	3.3	0.123	58.3
Little Creek Reservoir (2)	Virginia	37.350237610	–76.840561190	0.014	0.7	0.090	45.6
Little Ocmulgee Lake	Georgia	32.086523620	–82.895471580	0.022	0.6	0.111	60.8
Long Meadow Pond	Connecticut	41.654048000	–73.209854130	0.037	4.6	0.202	50.8
Loughberry Lake	New York	43.092181600	–73.767909200	0.016	3.2	0.099	38.3
Maple Lake (2)	New Jersey	39.406018010	–74.776604930	0.032	1.7	0.036	40.2
Messerschmidt Pond	Connecticut	41.338351600	–72.483821000	0.019	3.4	0.177	44.9
Mossy Lake	Georgia	32.478223820	–83.643906780	0.053	1.0	0.213	55.4
Mott Lake	North Carolina	35.051065610	–79.206614790	0.058	1.3	0.084	41.8
Mount Hope Lake (3)	New Jersey	40.924645470	–74.533107790	0.017	2.8	0.289	70.2
Norton Reservoir (2)	Massachusetts	41.985441670	–71.188869800	0.035	0.5	0.124	40.1
Scituate Reservoir	Rhode Island	41.833574670	–71.593471800	0.017	4.1	0.328	52.7
Ski Lake	Alabama	33.292077480	–87.146819780	0.029	3.4	0.187	39.8
Slack Reservoir	Rhode Island	41.868656670	–71.553843730	0.029	3.0	0.165	37.9
Vaughn Pond	South Carolina	34.320169280	–80.632973520	0.039	3.5	0.065	46.9
Wrights Pond (2)	Virginia	38.216791410	–77.663228720	0.051	1.5	0.022	55.4

Table 25. Headwater reservoirs identified in the chlorophyll *a* regression tree for endpoint four (eutrophic) in figure 7.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	TSI(*CHL*)
Beaver Dam Reservoir	Virginia	37.31324041	–79.81543472	0.471	0.115	47.0
Buckhorn Reservoir	North Carolina	35.69098968	–78.12002372	1.116	0.096	62.3
Gantt Reservoir	Alabama	31.40342309	–86.47953398	0.976	0.064	53.4
Gorton Pond	Rhode Island	41.70358880	–71.46116500	1.657	0.065	50.7
Graham-Mebane Lake	North Carolina	36.09513561	–79.33590192	1.064	0.118	56.5
Lake Allatoona (2)	Georgia	34.16377961	–84.72721171	1.001	0.076	47.1
Lake Burnt Mills	Virginia	36.84083228	–76.62743512	1.443	0.137	57.8
Lake Fisher	North Carolina	35.48632061	–80.57827712	1.641	0.132	62.2
Lake Lanier	Virginia	36.65613028	–79.84066112	1.449	0.093	48.3
Lake Marion	South Carolina	33.45532668	–80.16423312	0.542	0.069	55.6
Lake Montclair	Virginia	38.61012967	–77.34286219	0.906	0.091	49.5
Lake Nephawin	Pennsylvania	41.63328380	–76.84364572	1.741	0.077	44.6
Lake Orange	North Carolina	36.14612821	–79.14926332	1.365	0.154	58.7
Lees Lake	Alabama	33.88106148	–85.93313531	1.518	0.075	58.7
Manassas	Virginia	38.76343741	–77.62268892	1.407	0.108	52.7
McMath Millpond (2)	Georgia	32.07357908	–84.28822071	0.898	0.097	62.5
Merle-Smith Lake	Virginia	37.99744987	–78.17659472	0.744	0.067	65.9
Salco Lake	Alabama	30.97246202	–88.05048657	0.367	0.138	32.9
Swan Lake (2)	Georgia	33.58010528	–84.20447738	1.133	0.142	65.9
Swimming River Reservoir	New Jersey	40.31904787	–74.11517160	1.114	0.103	53.7
Union Pond	Connecticut	41.79991587	–72.52818873	1.775	0.124	57.6
Weiss Reservoir	Alabama	34.13262221	–85.79426658	0.894	0.075	66.2
Wheeler's Pond	Virginia	37.11828348	–77.62753852	0.814	0.075	71.6

Table 26. Headwater reservoirs identified in the chlorophyll *a* regression tree for endpoint five (eutro-hypereutrophic) in figure 7.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	TSI(*CHL*)
Bald Run Reservoir	Virginia	38.48914267	–78.00521712	2.225	0.154	61.9
Beaver Pond (4)	Virginia	37.29686101	–77.88250279	2.030	0.127	66.5
Concord Pond	Delaware	38.64255861	–75.55407739	3.226	0.127	55.5
Coursey Pond	Delaware	38.98123467	–75.52987479	3.399	0.064	77.3
J T Budd Pond	Florida	30.38884182	–84.64659258	2.161	0.114	70.9
Johnsons Pond	Maryland	38.37225367	–75.60249059	3.734	0.154	77.5
Lake George (2)	Alabama	34.22274528	–86.83777318	2.672	0.098	48.7
Lake Purdy	Alabama	33.46009342	–86.66825158	5.155	1.259	55.7
McColley Pond	Delaware	38.96711101	–75.49341399	3.677	0.073	64.0
Needwood Lake	Maryland	39.11430787	–77.12951532	2.194	0.123	62.6
Orange Reservoir (2)	New Jersey	40.75908187	–74.28646013	2.343	0.156	67.7
Piney Run Reservoir	Maryland	39.37679547	–76.89043992	2.628	0.117	40.9
Red Mill Pond (2)	Delaware	38.75994767	–75.20394119	3.995	0.073	77.1
Reed Bingham Park Lake	Georgia	31.16169062	–83.54321271	2.641	0.158	57.2
Shelly Lake	North Carolina	35.85653561	–78.66091319	2.274	0.146	70.1
Silver Lake Dover	Delaware	39.16809767	–75.52177213	3.318	0.112	83.3
Struble Lake (2)	Pennsylvania	40.10802820	–75.86449679	6.180	0.205	63.1
Trussum Pond	Delaware	38.52521327	–75.51164659	3.755	0.195	57.5
Unicorn Mill Pond	Maryland	39.24769201	–75.86012479	3.940	0.224	43.4
Walker Lake	Pennsylvania	40.79669247	–77.19614699	2.221	0.076	66.1

Downstream Reservoirs

Of the 48 downstream reservoirs characterized by 60 chlorophyll *a* sample concentrations, 24 were classified as mesotrophic, 18 eutrophic, and 6 eutro-hypereutrophic (fig. 8). Total phosphorus flow-weighted concentration of the inflow load estimate explained 25 percent of the variability in log10 chlorophyll *a* concentrations, followed by total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate (19 percent), flow-weighted total nitrogen concentration of the inflow load estimate (17 percent), relative depth (11 percent), shoreline development ratio (11 percent), morphometric factor (10 percent), development of volume (4 percent), and basin permanence (3 percent). The model-boosting functional gradient descent algorithm separated the recursive partitioning tree into four nodes and five endpoints by using the minimum number of observations in a node considered for splitting, which was set at 20.

Details of the downstream reservoirs identified within each endpoint are included in tables 27–31. The individual chlorophyll *a* or mean chlorophyll *a* concentration (in the case where two or more chlorophyll *a* concentrations were recorded) for each downstream reservoir was converted to Carlson's chlorophyll *a* trophic state value (eq. 8) for validation. In addition, the chlorophyll *a* concentrations for each endpoint were averaged and assigned a trophic state (TSI[*CHL*], fig. 8).

As shown in figure 8, downstream reservoirs with a total phosphorus flow-weighted concentration of the inflow load estimate less than 0.059 mg/L and a development of volume greater than or equal to 1.073 had the lowest chlorophyll *a* concentrations. These were the downstream reservoirs with flatter bottoms, less cone shaped. Chlorophyll *a* concentrations were highest in downstream reservoirs with total phosphorus flow-weighted concentrations of the inflow load estimate greater than or equal to 0.059 mg/L and total nitrogen flow-weighted concentrations of the inflow load estimate greater than or equal to 1.775 mg/L. The total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate played a role for downstream reservoirs with flow-weighted total nitrogen concentrations of the inflow load estimate less than 1.775 mg/L and total phosphorus concentrations of the inflow load estimate greater than or equal to 0.059 mg/L.

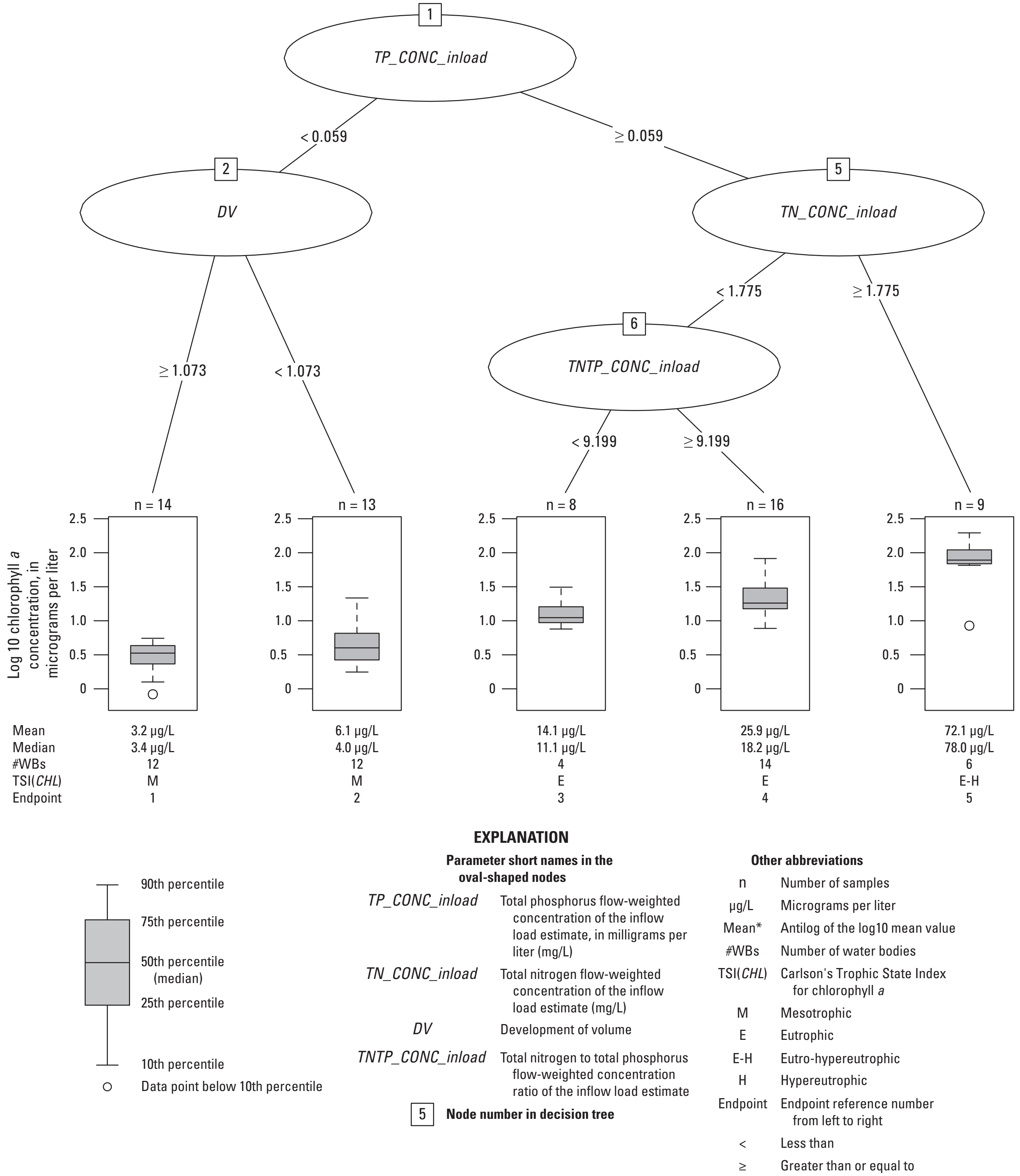


Figure 8. Diagram showing a chlorophyll *a* regression tree for downstream reservoirs.

Table 27. Downstream reservoirs identified in the chlorophyll *a* regression tree for endpoint one (mesotrophic) in figure 8.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Development of volume	TSI(*CHL*)
Besse Bog Reservoir	Massachusetts	41.80847460	–70.64241760	0.006	1.506	47.4
Coneross Creek Reservoir	South Carolina	34.72319988	–83.10458858	0.031	1.089	45.3
Groton Reservoir	Connecticut	41.35043667	–72.03650873	0.019	1.108	32.9
Lake Altoona	Pennsylvania	40.49296647	–78.45661759	0.016	1.171	28.8
Lake Stockwell-19	New Jersey	39.86291721	–74.80363219	0.016	1.233	43.6
Little Lake	Maine	44.78414740	–67.19145667	0.005	1.077	35.7
Middle Chain Pond	Maine	45.22046073	–68.07062400	0.004	1.111	42.0
Morris Reservoir (3)	Connecticut	41.67475140	–73.14349713	0.031	1.092	41.8
Sconti Lake	Georgia	34.45104308	–84.28569278	0.038	1.495	45.0
Second Buttermilk Pond	Maine	45.32849713	–69.26694807	0.007	1.378	40.4
South Pacolet River Reservoir Number One	South Carolina	35.11106008	–81.96997492	0.031	1.101	45.8
Spaulding Pond	New Hampshire	43.37836353	–70.98390127	0.014	1.253	42.8

Table 28. Downstream reservoirs identified in the chlorophyll *a* regression tree for endpoint two (mesotrophic) in figure 8.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Development of volume	TSI(*CHL*)
Beltzville Dam	Pennsylvania	40.85129460	–75.63909473	0.022	0.822	46.2
Keech Pond	Rhode Island	41.90201800	–71.67669093	0.019	0.952	45.6
Lake Townsend	North Carolina	36.18933701	–79.73196512	0.058	0.835	55.5
Long Pond	Maine	45.31415460	–70.62642020	0.013	0.956	41.5
Mirror Lake	New Jersey	39.96822581	–74.57956959	0.033	1.069	60.8
Mott Lake	North Carolina	35.05106561	–79.20661479	0.058	0.946	40.7
Nickajack Lake	Tennessee	35.00009628	–85.69731378	0.049	0.536	40.2
Pachaug Pond	Connecticut	41.58226140	–71.92998840	0.027	0.979	40.9
Philpott Reservoir	Virginia	36.78138081	–80.02773832	0.0585	0.512	37.6
Pocono Lake	Pennsylvania	41.09597780	–75.54254893	0.013	0.876	49.0
Smith and Sayles Reservoir	Rhode Island	41.90201800	–71.67669093	0.019	0.952	45.6
Waller Mill Reservoir (2)	Virginia	37.30301428	–76.70195132	0.017	0.974	46.6

Table 29. Downstream reservoirs identified in the chlorophyll *a* regression tree for endpoint three (eutrophic) in figure 8.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate	TSI(*CHL*)
Lake Demopolis (2)	Alabama	32.52054008	–87.87913091	1.066	0.122	8.708	53.1
Rhodhiss (2)	North Carolina	35.77338108	–81.43794752	0.476	0.079	6.008	59.4
Lake Hickory (3)	North Carolina	35.82214701	–81.19285118	0.549	0.079	6.983	53.5
Falls Lake	North Carolina	35.94103148	–78.58072879	0.918	0.126	7.270	59.7

Table 30. Downstream reservoirs identified in the chlorophyll *a* regression tree for endpoint four (eutrophic) in figure 8.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate	TSI(*CHL*)
Beaverdam Lake	North Carolina	35.81493621	–78.53290072	1.099	0.073	15.061	73.9
City Lake	North Carolina	34.88294508	–79.69233539	0.879	0.061	14.426	57.2
Hennington Lake	Mississippi	31.29583249	–89.44115077	0.791	0.070	11.232	52.9
Holt Lake (3)	Alabama	33.25401442	–87.44933797	1.056	0.074	14.350	58.3
Jordan Lake	Alabama	32.61890522	–86.25686358	0.751	0.063	11.947	58.7
Lake Brandt	North Carolina	36.17273048	–79.83855119	1.400	0.102	13.751	59.0
Lake Monroe	Florida	28.83478422	–81.31901778	0.796	0.082	9.690	57.4
Lake Wylie	North Carolina	35.02035681	–81.00767752	0.640	0.065	9.839	64.0
Lay Reservoir	Alabama	32.61890522	–86.25686358	0.751	0.063	11.947	63.0
Logan Martin Lake	Alabama	33.42597982	–86.33653698	0.858	0.079	10.886	54.9
Pickwick Lake	Tennessee	34.79591921	–87.62492884	0.725	0.073	9.891	64.1
R E 'Bob' Woodruff Reservoir	Alabama	32.32431628	–86.78413758	0.719	0.066	10.883	64.6
Southern Pines Waterworks	North Carolina	35.21528021	–79.40105612	1.479	0.100	14.769	59.2
Tuckertown Reservoir	North Carolina	35.48482108	–80.17678299	1.396	0.135	10.303	60.2

Table 31. Downstream reservoirs identified in the chlorophyll *a* regression tree for endpoint five (eutro-hypereutrophic) in figure 8.

[mg/L, milligrams per liter; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	TSI(*CHL*)
Concord Pond	Delaware	38.64255861	–75.55407739	3.226	0.127	72.1
Coursey Pond	Delaware	38.98879441	–75.51097759	3.318	0.060	73.3
Lake Lee (2)	North Carolina	34.96593248	–80.51090979	2.617	0.193	75.6
Noxontown Pond (3)	Delaware	39.43391441	–75.68356033	2.278	0.116	70.5
Packanack Lake	New Jersey	40.93390807	–74.25638673	2.071	0.085	82.4
Swiggetts Pond	Delaware	38.86893187	–75.37844493	3.640	0.111	82.4

Microcystin

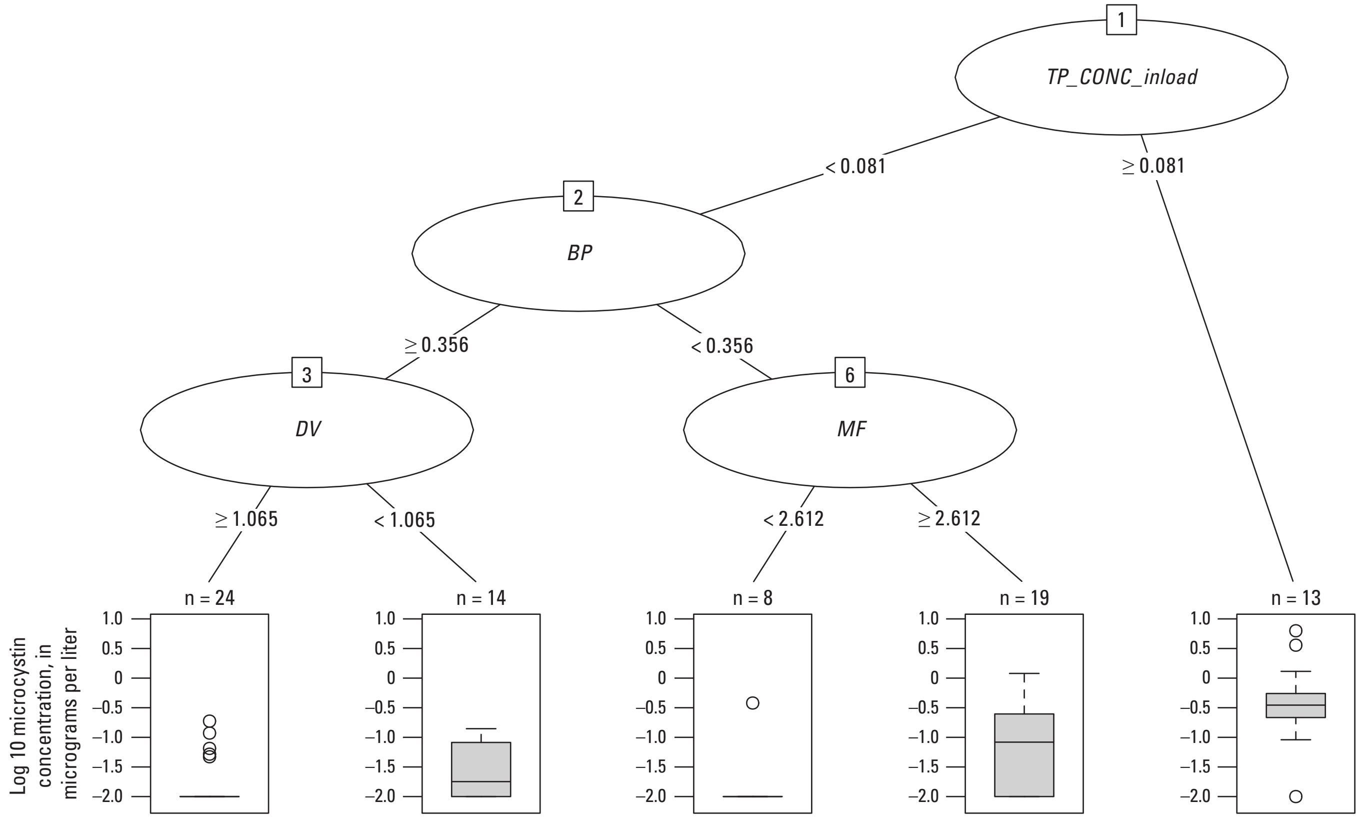
Microcystin samples were collected in open water rather than nearshore conditions. Therefore, these results may not be useful for nearshore predictions. All censored values (less than the minimum reporting levels for a variable) were adjusted to 0.01 microgram per liter for analysis.

Lakes

Of the 60 lakes characterized by 78 microcystin sample concentrations, 9 were classified as hypereutrophic (fig. 9). Lakes within the other four endpoints were a mix of mesotrophic and eutrophic systems, according to their mean Secchi depth and chlorophyll *a* trophic state values. Total phosphorus flow-weighted concentration of the inflow load estimate explained 21 percent of the variability in log10 microcystin concentrations, followed by relative depth (16 percent), morphometric factor (15 percent), total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate (15 percent), basin permanence (13 percent), total nitrogen flow-weighted concentration of the inflow estimate (13 percent), development of volume (3 percent), erosion ratio (2 percent), shoreline development ratio (2 percent), and flushing rate (1 percent). The model-boosting functional gradient descent algorithm separated the recursive partitioning tree into four nodes by using the minimum number of observations in a node considered for splitting, which was set at 25.

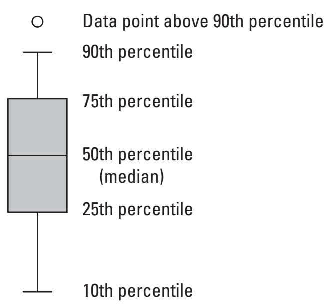
Details of the lakes identified within each endpoint are included in tables 32–36. The individual Secchi depth and concentration of chlorophyll *a* or mean Secchi depth and chlorophyll *a* (in the case where two or more were recorded) for each lake were converted into their respective TSI values (eqs. 7 and 8) for validation. In addition, trophic state values were averaged within each endpoint (TSI[*SD*], TSI[*CHL*], fig. 9).

As shown in figure 9, lakes with a total phosphorus flow-weighted concentration of the inflow load estimate greater than or equal to 0.081 mg/L had the highest microcystin concentrations, represented by lakes with hypereutrophic Secchi depth and chlorophyll *a* trophic state indices. This 0.081-mg/L split in total phosphorus flow-weighted concentration of the inflow load estimate was also present for chlorophyll *a* concentration in lakes (fig. 6). Basin permanence played a role for lakes with a total phosphorus flow-weighted concentration of the inflow load estimate less than 0.081 mg/L. Those with a basin permanence greater than or equal to 0.356 and a development of volume greater than or equal to 1.065 had the lowest microcystin concentrations. Trophic state indices for Secchi depth and chlorophyll *a* (eqs. 7 and 8) show that these lakes are mesotrophic, as are those with a development of volume less than 1.065. Morphometric factor had a role in lakes with a total phosphorus flow-weighted concentration of the inflow load estimate less than 0.081 mg/L and a basin permanence less than 0.356. These were the meso-eutrophic lakes. However, among the five endpoints, differences between collective trophic states do not appear to separate until total phosphorus flow-weighted concentration of the inflow load estimate becomes greater than or equal to 0.081 mg/L.



Mean	0.015 µg/L	0.028 µg/L	0.016 µg/L	0.074 µg/L	0.385 µg/L
Median	0.010 µg/L	0.021 µg/L	0.010 µg/L	0.095 µg/L	0.350 µg/L
#WBs	19	10	8	14	9
Mean TSI(*SD*)	M	M	M-E	M-E	H
Mean TSI(*CHL*)	M	M	M	M-E	H
Endpoint	1	2	3	4	5

EXPLANATION



Parameter short names in the oval-shaped nodes

TP_CONC_inload	Total phosphorus flow-weighted concentration of the inflow load estimate
BP	Basin permanence
DV	Development of volume
MF	Morphometric factor
3	**Node number in decision tree**

Other abbreviations

n	Number of samples	M	Mesotrophic
µg/L	Micrograms per liter	M-E	Meso-eutrophic
Mean*	Antilog of the log10 mean value	H	Hypereutrophic
#WBs	Number of water bodies	Endpoint	Endpoint reference number from left to right
TSI(*SD*)	Carlson's Trophic State Index for Secchi depth	<	Less than
TSI(*CHL*)	Carlson's Trophic State Index for chlorophyll *a*	≥	Greater than or equal to

Figure 9. Diagram showing a microcystin regression tree for lakes.

Table 32. Lakes identified in the microcystin regression tree for endpoint one in figure 9.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; n.a., data not available; (#), number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Basin permanence	Development of volume	TSI(*SD*)	TSI(*CHL*)
Anawana Lake	New York	41.69691967	–74.67307713	0.016	0.420	1.192	41.7	36.7
Chapman Pond	Rhode Island	41.38390040	–71.79087740	0.033	0.453	1.130	n.a.	45.2
Duck Lake	Maine	45.13796213	–68.11166580	0.007	4.334	1.076	34.4	30.9
Female Pond	Maine	45.74686393	–69.21582520	0.010	0.460	1.316	46.8	45.0
Fourth Debsconeag Lake	Maine	45.75377260	–69.06649160	0.008	1.898	1.247	34.6	32.6
Halfmile Pond	Maine	44.84720993	–68.42695427	0.005	0.429	1.370	47.0	41.9
Halfway Pond	Massachusetts	41.84569047	–70.61749947	0.004	0.632	1.173	54.0	64.4
Hinkley's Pond	Massachusetts	41.71206047	–70.09442620	0.005	0.691	1.250	49.3	53.8
Hudson Pond (2)	Maine	46.16757720	–69.01111460	0.006	0.617	1.217	55.1	52.2
Island Pond (2)	Vermont	44.81305413	–71.88040553	0.021	1.568	1.085	36.4	41.4
Lake Parker (2)	Vermont	44.72551533	–72.22915933	0.040	1.220	1.169	42.2	44.7
Miles Pond (2)	Vermont	44.44618040	–71.79759793	0.021	0.870	1.125	38.3	31.8
Norwich Pond	Massachusetts	42.30156307	–72.83456433	0.021	1.056	1.092	44.4	46.5
Plainfield Pond	Massachusetts	42.54642100	–72.95535300	0.020	0.440	1.241	n.a.	30.8
Pleasant Lake	Maine	45.34433240	–67.92492987	0.007	3.003	1.075	36.2	36.4
Roseland Lake (2)	Connecticut	41.94518347	–71.94881040	0.027	0.359	1.159	57.0	63.1
Spring Lake	Maine	45.22190013	–68.21820660	0.006	1.123	1.142	38.3	35.6
West Hill Pond	Connecticut	41.89019947	–73.03671040	0.027	1.222	1.167	31.5	34.9
Wononpakook Lake	Connecticut	41.92932320	–73.45468860	0.028	0.861	1.186	41.3	44.6

Table 33. Lakes identified in the microcystin regression tree for endpoint two in figure 9.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Basin permanence	Development of volume	TSI(*SD*)	TSI(*CHL*)
Cooper Lake	New York	42.06272280	–74.17413553	0.023	1.016	1.054	37.2	33.8
Crescent Lake	Florida	29.53292869	–81.55607632	0.062	0.468	0.997	66.2	70.0
Lake Champlain	Vermont	45.01079380	–73.34532973	0.057	17.434	0.635	43.9	42.6
Lake Waramaug (2)	Connecticut	41.68300840	–73.35341680	0.031	1.511	0.961	42.2	49.0
Little Big Wood Pond	Maine	45.63096180	–70.33293860	0.012	2.594	1.003	44.5	39.8
Lower Middle Branch Pond (2)	Maine	44.86682033	–68.22573547	0.003	0.578	1.044	43.5	39.2
Maidstone Lake	Vermont	44.66712320	–71.64996220	0.011	3.531	1.033	29.1	30.8
Peaked Mountain Pond (2)	Maine	44.77770160	–67.70218841	0.006	0.461	1.017	37.6	33.9
Skitacook Lake	Maine	46.01997460	–68.06097807	0.011	0.992	1.020	42.4	38.6
Tilden Pond (2)	Maine	44.36192613	–69.10414607	0.014	0.450	1.042	45.0	45.8

Table 34. Lakes identified in the microcystin regression tree for endpoint three in figure 9.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; n.a., data not available]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Basin permanence	Morphometric factor	TSI(*SD*)	TSI(*CHL*)
Catfish Lake	North Carolina	34.92515821	–77.11213959	1.41×10^{-6}	0.118	0.135	77.3	58.6
Derby Lake	Vermont	44.94997533	–72.11835893	0.045	0.279	2.033	36.7	38.9
Fourth Machias Lake	Maine	45.16874213	–67.97366907	0.005	0.318	0.518	53.4	36.6
Long Pond	New York	44.34754793	–74.40093260	0.013	0.330	2.501	41.1	42.2
Sip Pond	New Hampshire	42.72931720	–72.10023633	0.013	0.209	1.644	49.0	39.8
Tomhegan Pond	Maine	45.78368973	–69.89469527	0.008	0.348	2.509	n.a.	50.9
White Lake	Florida	30.31497822	–82.87553392	0.080	0.078	1.327	n.a.	57.7
Yawgoo Pond	Rhode Island	41.50751340	–71.56953240	0.024	0.352	2.498	46.9	43.6

Table 35. Lakes identified in the microcystin regression tree for endpoint four in figure 9.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one; n.a., data not available]

Lake name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	Basin permanence	Morphometric factor	TSI(*SD*)	TSI(*CHL*)
Adder Pond (2)	New Hampshire	43.4472420	–71.8059257	0.016	0.234	7.743	56.4	48.7
Beardsley Pond (2)	Connecticut	41.8941246	–73.4504229	0.029	0.195	9.655	55.9	50.6
Brindle Pond	New Hampshire	43.3684800	–71.2499800	0.017	0.264	3.537	51.8	42.5
Crooked Pond	New Hampshire	43.2939110	–71.4246439	0.017	0.162	6.183	56.4	56.6
Dan Forth Ponds (2)	New Hampshire	43.8349730	–71.0956105	0.008	0.134	5.286	42.1	36.8
Horseshoe Lake	Maine	44.8701737	–67.5784041	0.006	0.112	5.762	37.8	n.a.
Lake Kenosia	New Hampshire	41.3825819	–73.4980568	0.054	0.232	5.045	57.4	60.9
Laurel Lake (2)	Pennsylvania	41.6921004	–75.1285832	0.031	0.328	6.652	56.3	61.8
Little Greenough Pond	New Hampshire	44.8385686	–71.1373987	0.006	0.272	8.632	48.4	43.4
Little Watchie Pond	Maine	43.7785634	–70.6099483	0.004	0.126	4.108	52.1	46.1
Long Pond (2)	New Hampshire	42.6846061	–71.3686232	0.031	0.304	3.013	54.3	56.5
Long Pond	Massachusetts	41.6546828	–70.3352753	0.006	0.082	2.715	48.0	53.6
Trafton Pond	Maine	43.8456248	–70.8941852	0.010	0.314	6.956	41.9	57.7
Webster Pond	Maine	45.4428559	–68.1894758	0.009	0.182	6.645	45.4	44.0

Table 36. Lakes identified in the microcystin regression tree for endpoint five in figure 9.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one; n.a., data not available]

Lake name	State	Outreach latitude (decimal degrees)	Outreach longitude (decimal degrees)	Total phosphorus flow-weighted concentration of the inflow load estimate (mg/L)	TSI(*SD*)	TSI(*CHL*)
Lake Apopka (2)	Florida	28.67289429	–81.67871172	0.230	85.0	76.7
Lake Griffin (2)	Florida	28.86147702	–81.88672892	0.108	70.7	77.7
Lake Kittamagundi (2)	Maryland	39.21207761	–76.85496819	0.137	71.5	67.4
Lake Monroe	Florida	28.83478422	–81.31901778	0.082	67.8	64.2
Lake Seminole	Florida	27.83987302	–82.78127498	0.322	75.1	76.2
Lake Tarpon	Florida	28.07865662	–82.70971972	0.117	66.2	66.5
Lake Thonotosass	Florida	28.06809429	–82.26869452	0.253	81.2	82.0
Leonard Pond (2)	Maryland	38.42298901	–75.56371879	0.118	n.a.	64.3
Trout Lake	Florida	28.86485669	–81.68633538	0.156	71.5	75.6

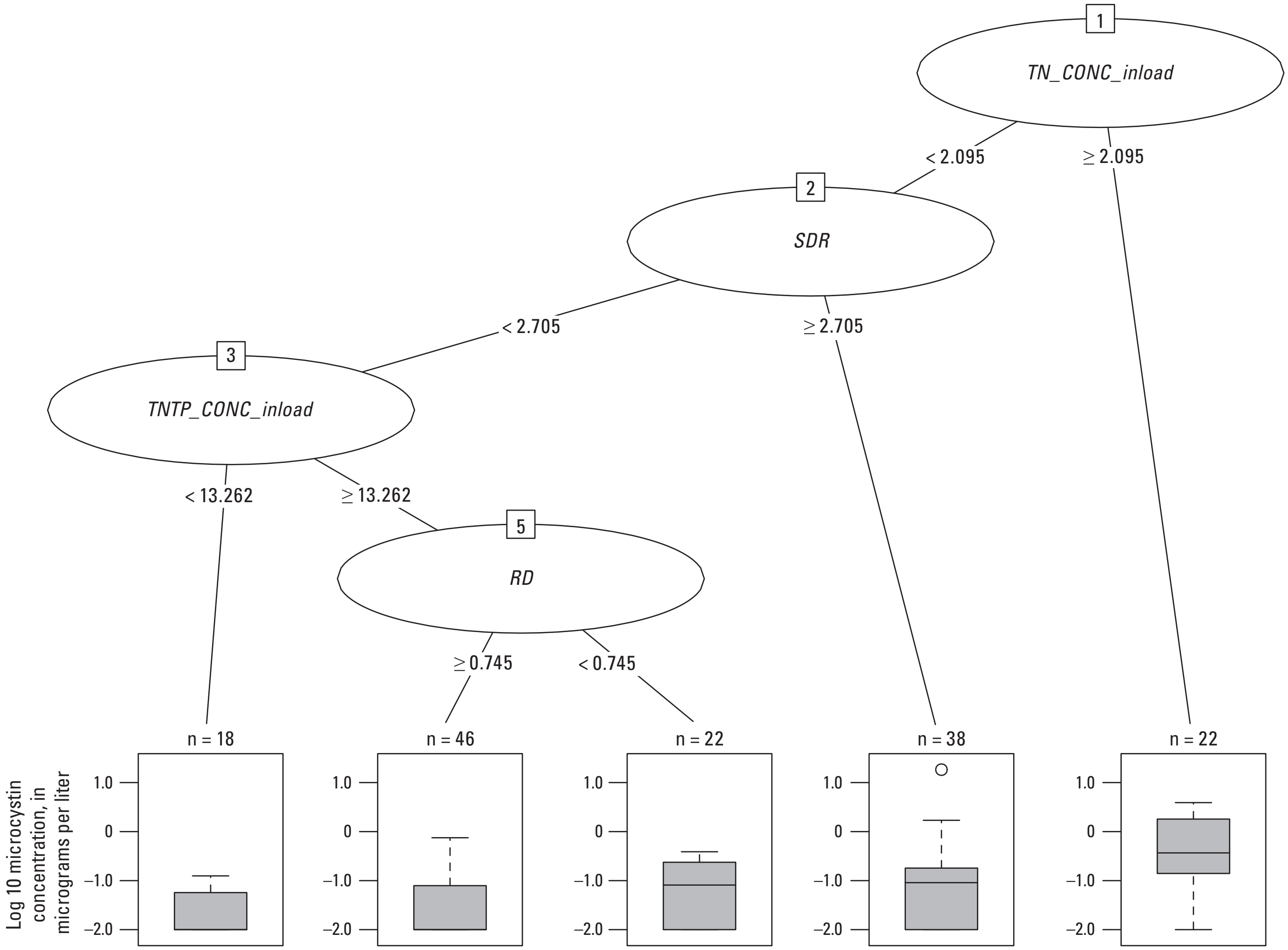
Headwater Reservoirs

Of the 113 headwater reservoirs characterized by 147 microcystin sample concentrations, 18 were classified as eutro-hypereutrophic (endpoint 5, fig. 10), having a total nitrogen flow-weighted concentration of the inflow load estimate greater than or equal 2.095 mg/L. Headwater reservoirs within the other four endpoints were a mix of mesotrophic and eutrophic systems, according to their mean Secchi depth and chlorophyll *a* trophic state index values.

Total nitrogen flow-weighted concentration of the inflow load estimate explained 42 percent of the variability in log10 microcystin concentrations, followed by total phosphorus flow-weighted concentration of the inflow load estimate (17 percent), shoreline development ratio (10 percent), relative depth (7 percent), morphometric factor (6 percent), erosion ratio (6 percent), development of volume (5 percent), total nitrogen to total phosphorus flow-weighted concentration ratio of the inflow load estimate (4 percent), basin permanence (3 percent), and flushing rate (2 percent). The model-boosting functional gradient descent algorithm separated the recursive partitioning tree into four nodes by using the minimum number of observations in a node considered for splitting, which was set at 55.

Details of the headwater reservoirs identified within each endpoint are included in tables 37–41. The individual Secchi depth and chlorophyll *a* concentrations or mean Secchi depth and chlorophyll *a* concentrations (in the case where two or more were recorded) for each headwater reservoir were converted into their respective Carlson's trophic state value (eqs. 7 and 8) for validation. In addition, trophic state values were averaged for Secchi depth and chlorophyll *a* concentrations within each endpoint (mean TSI[*SD*] and TSI[*CHL*], fig. 10).

As shown in figure 10, headwater reservoirs with a total nitrogen flow-weighted concentration of the inflow load estimate greater than or equal to 2.095 mg/L had the highest microcystin concentrations, represented by those with eutro-hypereutrophic trophic state indices. The endpoints with the lowest microcystin concentrations were those with a total nitrogen flow-weighted concentration of the inflow load estimate less than 2.095 mg/L, a shoreline development ratio less than 2.705, and a total nitrogen to total phosphorus concentration ratio of the inflow load estimate less than 13.262. However, the trophic state indices indicate that these are eutrophic headwater reservoirs on the basis of their collective average TSI(*SD*) and TSI(*CHL*) values, suggesting microcystin may not be present in all eutrophic headwater reservoirs.



Mean	0.018 µg/L	0.027 µg/L	0.050 µg/L	0.070 µg/L	0.318 µg/L
Median	0.010 µg/L	0.010 µg/L	0.082 µg/L	0.091 µg/L	0.151 µg/L
#WBs	15	35	15	30	18
Mean TSI(*SD*)	E	M	M-E	E	E-H
Mean TSI(*CHL*)	E	M	M	M	E-H
Endpoint	1	2	3	4	5

EXPLANATION

○ Data point above 90th percentile
90th percentile
75th percentile
50th percentile (median)
25th percentile
10th percentile

Parameter short names in the oval-shaped nodes

TN_CONC_inload	Total nitrogen flow-weighted concentration of the inflow load estimate
SDR	Shoreline development ratio
TNTP_CONC_inload	The total nitrogen to total phosphorus flow-weighted concentration of the inflow load estimate ratio
RD	Relative depth
3	**Node number in decision tree**

Other abbreviations

n	Number of samples	E	Eutrophic
µg/L	Micrograms per liter	M	Mesotrophic
Mean*	Antilog of the log10 mean value	M-E	Meso-eutrophic
#WBs	Number of water bodies	E-H	Eutro-hypereutrophic
TSI(*SD*)	Carlson's Trophic State Index for Secchi depth	Endpoint	Endpoint reference number from left to right
TSI(*CHL*)	Carlson's Trophic State Index for chlorophyll *a*	<	Less than
		≥	Greater than or equal to

Figure 10. Diagram showing a microcystin regression tree for headwater reservoirs.

Table 37. Headwater reservoirs identified in the microcystin regression tree for endpoint one in figure 10.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outreach latitude (decimal degrees)	Outreach longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Total nitrogen to total phosphorus concentration ratio of the flow-weighted inflow load estimate	Shoreline development ratio	TSI(*SD*)	TSI(*CHL*)
Beaver Dam Reservoir	Virginia	37.31324041	–79.81543472	0.471	4.105	2.648	40.2	47.0
Crane Pond (2)	South Carolina	33.03726648	–79.98063539	0.273	7.098	1.293	70.5	56.7
Holiday Lake	Virginia	37.39143848	–78.63582672	0.484	8.769	2.478	43.0	44.1
Island Pond	New Hampshire	43.17163793	–72.05954113	0.315	12.884	1.949	36.1	35.8
Kings Mountain #1 Lake (2)	North Carolina	35.20142181	–81.34949852	0.332	9.460	1.644	41.9	34.9
Lake Greeley	Pennsylvania	41.41542407	–75.01769439	0.385	12.391	2.239	61.8	54.7
Lake Rim	North Carolina	35.03120981	–79.04147679	0.623	10.578	1.991	58.6	58.2
Lake Tahoma	North Carolina	35.72289408	–82.07999518	0.218	7.090	1.906	43.6	37.6
McMath Millpond (2)	Georgia	32.07357908	–84.28822071	0.898	9.288	2.380	60.0	62.5
Merle-Smith Lake	Virginia	37.99744987	–78.17659472	0.744	11.087	1.835	58.7	65.9
Mott Lake	North Carolina	35.05106561	–79.20661479	0.472	8.157	2.576	49.7	40.7
Salco Lake	Alabama	30.97246202	–88.05048657	0.367	2.658	1.979	54.6	32.9
Swan Lake	Georgia	33.58010528	–84.20447738	1.133	7.986	2.284	60.8	65.9
Weiss Reservoir	Alabama	34.13262221	–85.79426658	0.894	11.979	2.460	70.6	66.2
Wheeler's Pond	Virginia	37.11828348	–77.62753852	0.814	10.919	2.668	73.2	71.6

Table 38. Headwater reservoirs identified in the microcystin regression tree for endpoint two in figure 10.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one; n.a., data not available]

Reservoir name	State	Outreach latitude (decimal degrees)	Outreach longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Total nitrogen to total phosphorus concentration ratio of the flow-weighted inflow load estimate	Shoreline development ratio	Relative depth	TSI(*SD*)	TSI(*CHL*)
Back Lake	New Hampshire	45.08388480	–71.36416200	0.733	43.3	1.503	1.096	46.5	41.3
Beach Pond	Rhode Island	41.58157987	–71.81793373	0.527	42.8	1.955	1.245	40.4	40.6
Bissonnette Pond	Connecticut	41.92254887	–72.22045480	0.626	20.9	1.811	1.620	50.0	53.6
Cusky Pond	Massachusetts	42.32378900	–72.09554260	1.216	32.2	1.443	1.368	62.2	58.3
Elkhorn Lake	Virginia	38.32728081	–79.22330012	0.492	43.5	1.204	6.041	39.3	39.5
Gorton Pond	Rhode Island	41.70358880	–71.46116500	1.657	25.3	1.126	1.007	46.1	50.7
Halls Pond	Connecticut	41.83728400	–72.11413360	0.530	23.6	1.538	1.388	41.0	40.8
Haynes Reservoir	Massachusetts	42.54266987	–71.81759893	0.538	31.1	1.470	1.480	n.a.	37.8
Howard Pond	Maine	44.50598600	–70.71488287	0.233	19.9	1.551	2.938	38.7	32.4
Jolly Pond (2)	Virginia	37.29717681	–76.81955759	0.464	22.6	2.494	0.756	64.7	64.5
Lake Habeeb (3)	Maryland	39.70123487	–78.66278399	0.799	15.4	2.356	0.908	43.2	40.0
Lake Lanier	Virginia	36.65613028	–79.84066112	1.449	15.6	1.832	0.988	47.1	48.3
Lake Nephawin	Pennsylvania	41.63328380	–76.84364572	1.741	22.7	1.219	1.674	48.0	44.6
Lake Stanmore	Pennsylvania	41.97358100	–75.88156933	0.628	25.9	1.115	2.733	46.5	51.7
Lake Tranquility (3)	New Jersey	40.94915467	–74.78603879	0.818	21.4	1.735	0.816	59.3	58.9
Long Meadow Pond	Connecticut	41.65404800	–73.20985413	0.943	25.4	2.426	0.922	46.8	50.8
Messerschmidt Pond	Connecticut	41.33835160	–72.48382100	0.495	25.7	1.780	0.775	48.3	44.9
Mount Hope Lake (3)	New Jersey	40.92464547	–74.53310779	0.628	36.4	1.796	0.769	n.a.	72.0
Pleasant Lake	Maine	44.00951813	–70.52283867	0.346	30.6	1.779	0.773	35.3	36.5
Riga Lake	Connecticut	42.01791447	–73.47768820	0.618	24.1	1.661	1.362	27.4	27.0
Round Valley Reservoir	New Jersey	40.61086507	–74.84524579	0.406	20.1	1.373	1.787	46.8	46.5
Scituate Reservoir	Rhode Island	41.83357467	–71.59347180	0.506	30.0	1.959	1.014	58.0	52.7
Sequoyah Lake	Georgia	34.54423768	–84.37114038	0.830	19.3	1.872	1.473	39.9	33.5
Ski Lake	Alabama	33.29207748	–87.14681978	0.660	22.6	2.218	0.810	48.3	39.8
Slatersville Reservoirs (3)	Rhode Island	41.99438067	–71.59482480	0.568	19.2	1.410	1.225	45.1	45.6
Sly Pond	New York	43.45091833	–73.59341980	0.388	19.5	1.527	1.688	32.4	33.5
Spoonwood Pond	New Hampshire	42.99408540	–72.06537920	0.333	19.6	1.538	2.133	30.7	25.8
Spring Creek Lake	Virginia	37.21370788	–78.61656019	1.035	18.5	1.988	1.113	52.7	54.5
Starlight Lake	Pennsylvania	41.90701620	–75.33349139	0.839	17.9	1.488	2.147	40.0	42.5
Stump Pond	Rhode Island	41.69995907	–71.63711620	0.313	25.2	1.570	0.875	n.a.	41.2
Table Rock Reservoir (2)	South Carolina	35.06469841	–82.67160492	0.569	119.2	2.511	1.992	41.0	33.2
Tipton	Pennsylvania	40.67554347	–78.32649772	0.486	55.5	1.587	1.972	34.8	21.5
Wallace Pond	Massachusetts	42.70302060	–71.92482860	0.619	31.4	1.423	1.220	56.9	46.8
West Hill Pond	Connecticut	41.89019947	–73.03671040	0.678	25.2	1.446	1.427	32.3	34.7
Willard Pond (2)	New Hampshire	43.01833240	–72.01866020	0.327	13.6	1.287	2.191	31.7	28.2

Table 39. Headwater reservoirs identified in the microcystin regression tree for endpoint three in figure 10.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one; n.a., data not available]

Reservoir name	State	Outreach latitude (decimal degrees)	Outreach longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Shoreline development ratio	Total nitrogen to total phosphorus concentration ratio of the flow-weighted inflow load estimate	Relative depth	TSI(*SD*)	TSI(*CHL*)
Beaver Pond (4)	Virginia	37.29686101	–77.88250279	2.030	2.143	16.027	0.692	63.4	66.5
Belleville Pond (2)	Rhode Island	41.55958607	–71.47316660	0.735	2.146	21.822	0.519	59.2	54.7
Bowdish Reservoir	Rhode Island	41.92094947	–71.77781893	0.464	2.231	26.698	0.569	45.7	9.2
Emmit Wood Lake (2)	Alabama	31.61972262	–88.34816071	0.370	1.477	15.397	0.733	70.8	72.5
Harrison Lake	Virginia	37.34418641	–77.18614619	0.801	2.025	18.623	0.248	71.2	24.5
Lake Naomi	Pennsylvania	41.10863927	–75.47318433	0.846	2.401	54.359	0.435	0.0	11.2
Lees Lake	Alabama	33.88106148	–85.93313531	1.518	2.380	20.263	0.383	66.2	28.1
Little Ocmulgee Lake	Georgia	32.08652362	–82.89547158	0.346	1.967	15.807	0.109	62.3	30.2
Loughberry Lake	New York	43.09218160	–73.76790920	0.609	2.329	38.336	0.673	44.7	7.7
Maple Lake (2)	New Jersey	39.40601801	–74.77660493	0.451	1.608	14.121	0.279	0.3	63.7
Mossy Lake	Georgia	32.47822382	–83.64390678	0.768	1.293	14.401	0.224	59.6	24.8
Norton Reservoir (2)	Massachusetts	41.98544167	–71.18886980	0.833	2.496	23.796	0.151	n.a.	9.5
Slack Reservoir	Rhode Island	41.86865667	–71.55384373	1.161	2.553	40.187	0.690	55.9	7.3
Union Pond	Connecticut	41.79991587	–72.52818873	1.775	1.534	14.354	0.703	54.2	27.0
Vaughn Pond	South Carolina	34.32016928	–80.63297352	0.571	1.691	14.468	0.586	58.6	16.3

Table 40. Headwater reservoirs identified in the microcystin regression tree for endpoint four in figure 10.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outreach latitude (decimal degrees)	Outreach longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Shoreline development ratio	TSI(*SD*)	TSI(*CHL*)
Beltzville Lake	Pennsylvania	40.85129460	–75.63909473	0.889	5.02	40.4	48.1
Blue Ridge Lake	Georgia	34.88245241	–84.28048678	0.377	7.74	43.9	38.7
Breckinridge Reservoir	Virginia	38.53609741	–77.39147552	0.395	2.80	54.5	48.8
Buckhorn Reservoir	North Carolina	35.69098968	–78.12002372	1.116	3.06	62.3	62.3
Cheatham Pond	Virginia	37.29864448	–76.61630552	0.632	3.88	77.8	72.3
Diascund Creek Reservoir	Virginia	37.43014121	–76.89440559	0.601	7.73	66.2	63.1
Flat River Reservoir (2)	Rhode Island	41.69451820	–71.59568620	0.449	4.48	46.5	38.4
Flying Pond	Maine	44.51498733	–69.99321840	0.396	2.74	47.7	39.0
Gantt Reservoir	Alabama	31.40342309	–86.47953398	0.976	4.62	39.8	37.0
Graham-Mebane Lake	North Carolina	36.09513561	–79.33590192	1.064	7.33	60.3	53.4
Highland Lake (2)	New Hampshire	43.07887960	–72.09360413	0.395	4.09	44.4	43.8
Lackawanna Lake	Pennsylvania	41.55706880	–75.71780319	1.243	3.08	43.5	43.6
Lake Allatoona (2)	Georgia	34.16377961	–84.72721171	1.001	12.11	48.6	47.1
Lake Burnt Mills	Virginia	36.84083228	–76.62743512	1.443	7.91	52.9	62.5
Lake Fisher	North Carolina	35.48632061	–80.57827712	1.641	3.40	47.9	46.4
Lake Lurleen	Alabama	33.28664102	–87.68496351	0.403	3.34	49.3	47.9
Lake Marion	South Carolina	33.45532668	–80.16423312	0.542	10.62	59.3	57.8
Lake Montclair	Virginia	38.61012967	–77.34286219	0.906	3.19	64.5	62.2
Lake Orange	North Carolina	36.14612821	–79.14926332	1.365	3.75	52.8	48.3
Lewis Smith Reservoir	Alabama	33.94242841	–87.10581998	1.199	26.63	60.7	55.6
Lineville Lake (2)	Alabama	33.31912502	–85.80792718	0.487	2.83	52.7	44.9
Little Creek Reservoir (2)	Virginia	37.35023761	–76.84056119	0.636	7.95	52.6	52.1
Manassas	Virginia	38.76343741	–77.62268892	1.407	4.52	52.8	41.7
Raystown Lake	Pennsylvania	40.43355054	–78.00711259	1.604	9.35	52.6	48.1
Savage River Reservoir	Maryland	39.50767201	–79.13409419	1.274	3.42	46.7	45.4
Sebasticook Lake (2)	Maine	44.83557700	–69.27198280	0.557	3.06	47.5	50.2
Swimming River Reservoir	New Jersey	40.31904787	–74.11517160	1.114	4.37	54.0	52.7
Tully Lake	Massachusetts	42.64272413	–72.22331540	0.350	2.74	43.9	43.8
Winnisquam Lake (2)	New Hampshire	43.48068553	–71.53552060	0.149	3.02	33.1	34.6
Wrights Pond (2)	Virginia	38.21679141	–77.66322872	0.752	3.01	50.2	51.3

Table 41. Headwater reservoirs identified in the microcystin regression tree for endpoint five in figure 10.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outreach latitude (decimal degrees)	Outreach longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	TSI(*SD*)	TSI(*CHL*)
Bald Run Reservoir	Virginia	38.48914267	–78.00521712	2.225	70.0	61.9
Concord Pond	Delaware	38.64255861	–75.55407739	3.226	57.3	63.8
Coursey Pond	Delaware	38.98123467	–75.52987479	3.399	75.5	75.3
J T Budd Pond	Florida	30.38884182	–84.64659258	2.161	66.2	70.9
Johnsons Pond	Maryland	38.37225367	–75.60249059	3.734	75.1	77.5
Lake George (2)	Alabama	34.22274528	–86.83777318	2.672	55.9	48.7
Lake Purdy	Alabama	33.46009342	–86.66825158	5.155	54.6	55.7
McColley Pond	Delaware	38.96711101	–75.49341399	3.677	62.0	64.0
Needwood Lake	Maryland	39.11430787	–77.12951532	2.194	64.1	62.6
Orange Reservoir (2)	New Jersey	40.75908187	–74.28646013	2.343	65.2	67.7
Piney Run Reservoir	Maryland	39.37679547	–76.89043992	2.628	39.3	40.9
Red Mill Pond (2)	Delaware	38.75994767	–75.20394119	3.995	79.4	77.1
Reed Bingham Park Lake	Georgia	31.16169062	–83.54321271	2.641	58.0	57.2
Shelly Lake	North Carolina	35.85653561	–78.66091319	2.274	78.6	70.1
Silver Lake Dover	Delaware	39.16809767	–75.52177213	3.318	77.8	83.3
Struble Lake (2)	Pennsylvania	40.10802820	–75.86449679	6.180	63.0	63.1
Trussum Pond	Delaware	38.52521327	–75.51164659	3.755	68.0	57.5
Walker Lake	Pennsylvania	40.79669247	–77.19614699	2.221	68.6	66.1

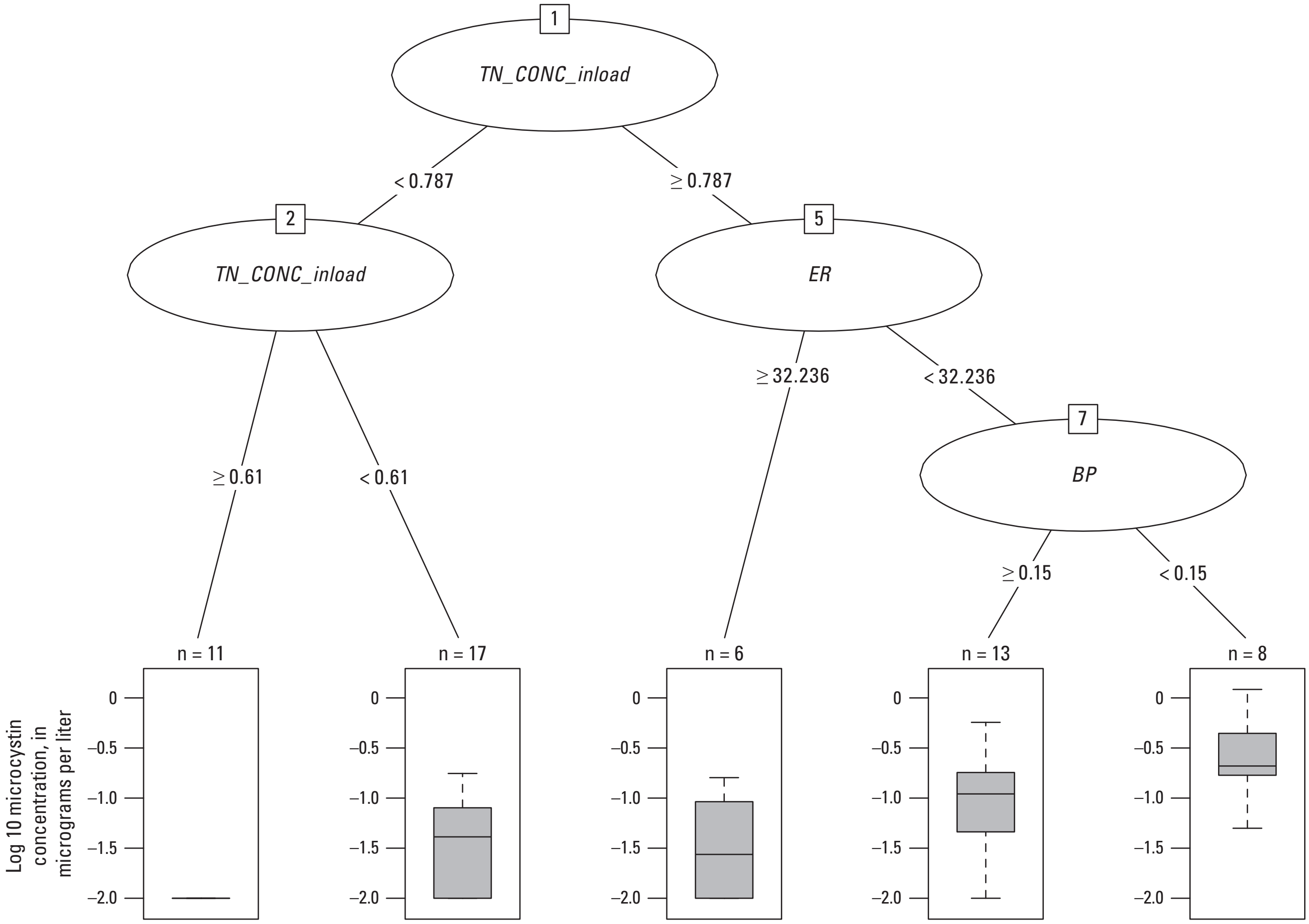
Downstream Reservoirs

Of the 43 downstream reservoirs characterized by 55 microcystin sample concentrations, 5 were classified as hypereutrophic (endpoint 5, fig. 11) having a total nitrogen flow-weighted concentration of the inflow load estimate greater than or equal to 0.787 mg/L, an erosion ratio less than 32.236, and a basin permanence less than 0.15. Downstream reservoirs in the other four endpoints were a mixture of mesotrophic to eutro-hypereutrophic systems.

Total nitrogen flow-weighted concentration of the inflow load estimate explained 27 percent of the variability in log10 microcystin concentrations, followed by the erosion ratio (14 percent), total phosphorus flow-weighted concentration of the inflow load estimate (12 percent), basin permanence (12 percent), the morphometric factor (11 percent), shoreline development ratio (10 percent), relative depth (6 percent), development of volume (5 percent), and flushing rate (3 percent). The model-boosting functional gradient descent algorithm separated the recursive partitioning tree into three nodes by using the minimum number of observations in a node considered for splitting, which was set at 18.

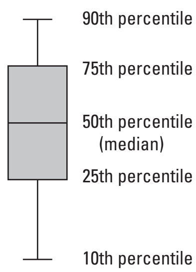
Details of the downstream reservoirs identified within each endpoint are included in tables 42–46. The individual Secchi depth and chlorophyll *a* concentrations or mean Secchi depth and chlorophyll *a* concentrations (in the case where two or more were recorded) for each downstream reservoir were converted into their respective Carlson's trophic state value (eqs. 7 and 8) for validation. In addition, trophic state values were averaged for Secchi depth, and concentrations of chlorophyll *a* and total phosphorus within each endpoint (mean TSI[*SD*] and TSI[*CHL*], fig. 11).

As shown in figure 11, downstream reservoirs with a total nitrogen flow-weighted concentration of the inflow load estimate greater than or equal to 0.787 mg/L, an erosion ratio less than 32.236, and a basin permanence less than 0.15, had the highest microcystin concentrations, represented by downstream reservoirs with hypereutrophic trophic state indices. The group of downstream reservoirs with the next highest microcystin concentrations were those with a total nitrogen flow-weighted concentration of the inflow load estimate greater than or equal to 0.787 mg/L, an erosion ratio less than 32.236, and a basin permanence greater than or equal to 0.15, represented by downstream reservoirs with eutrophic trophic state indices. Downstream reservoirs with the lowest microcystin concentrations were those with a total nitrogen flow-weighted concentration of the inflow load estimate greater than or equal to 0.610 mg/L but less than 0.787 mg/L, represented by downstream reservoirs with mesotrophic or meso-eutrophic trophic state indices.



Mean	0.010 µg/L	0.032 µg/L	0.032 µg/L	0.085 µg/L	0.249 µg/L
Median	0.010 µg/L	0.041 µg/L	0.043 µg/L	0.110 µg/L	0.210 µg/L
#WBs	11	13	5	9	5
Mean TSI(*SD*)	M-E	E	E-H	E	H
Mean TSI(*CHL*)	M	M	E	E	H
Endpoint	1	2	3	4	5

EXPLANATION



Parameter short names in the oval-shaped nodes

TN_CONC_inload	Total nitrogen flow-weighted concentration of the inflow load estimate
ER	Erosion ratio
BP	Basin permanence
5	**Node number in decision tree**

Other abbreviations

n	Number of samples
µg/L	Micrograms per liter
Mean*	Antilog of the log10 mean value
#WBs	Number of waterbodies
TSI(*SD*)	Carlson's Trophic State Index for Secchi depth
TSI(*CHL*)	Carlson's Trophic State Index for chlorophyll *a*
M-E	Meso-eutrophic
E	Eutrophic
E-H	Eutro-hypereutrophic
H	Hypereutrophic
Endpoint	Endpoint reference number from left to right
<	Less than
≥	Greater than or equal to

Figure 11. Diagram showing a microcystin regression tree for downstream reservoirs.

Table 42. Downstream reservoirs identified in the microcystin regression tree for endpoint one in figure 11.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	TSI(*SD*)	TSI(*CHL*)
Groton Reservoir	Connecticut	41.35043667	–72.03650873	0.781	39.1	32.9
Jordan Lake	Alabama	32.61890522	–86.25686358	0.751	51.9	57.4
Lake Altoona	Pennsylvania	40.49296647	–78.45661759	0.782	32.4	28.8
Lake Wylie	North Carolina	35.02035681	–81.00767752	0.640	50.2	54.9
Lay Reservoir	Alabama	32.61890522	–86.25686358	0.751	51.9	57.4
Nickajack Lake	Tennessee	35.00009628	–85.69731378	0.636	50.8	40.2
Philpott Reservoir	Virginia	36.78138081	–80.02773832	0.758	43.7	37.6
Pickwick Lake	Tennessee	34.79591921	–87.62492884	0.725	58.0	59.2
Pocono Lake	Pennsylvania	41.09597780	–75.54254893	0.639	53.4	49.0
R E 'Bob' Woodruff Reservoir	Alabama	32.32431628	–86.78413758	0.719	60.1	60.2
Sconti Lake	Georgia	34.45104308	–84.28569278	0.636	48.6	45.0

Table 43. Downstream reservoirs identified in the microcystin regression tree for endpoint two in figure 11.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	TSI(*SD*)	TSI(*CHL*)
Besse Bog Reservoir	Massachusetts	41.80847460	–70.64241760	0.287	43.0	47.4
Coneross Creek Reservoir	South Carolina	34.72319988	–83.10458858	0.474	54.6	45.3
Keech Pond	Rhode Island	41.90201800	–71.67669093	0.584	46.5	45.6
Lake Hickory (3)	North Carolina	35.82214701	–81.19285118	0.549	51.9	53.5
Long Pond	Maine	45.31415460	–70.62642020	0.379	39.5	41.5
Middle Chain Pond	Maine	45.22046073	–68.07062400	0.126	49.6	41.1
Mirror Lake	New Jersey	39.96822581	–74.57956959	0.578	62.3	60.8
Mott Lake	North Carolina	35.05106561	–79.20661479	0.472	49.7	40.7
Rhodhiss (2)	North Carolina	35.77338108	–81.43794752	0.476	57.2	59.4
Second Buttermilk Pond	Maine	45.32849713	–69.26694807	0.153	46.1	40.4
Smith and Sayles Reservoir	Rhode Island	41.90201800	–71.67669093	0.584	46.5	45.6
South Pacolet River Reservoir Number One	South Carolina	35.11106008	–81.96997492	0.499	55.7	45.8
Waller Mill Reservoir (2)	Virginia	37.30301428	–76.70195132	0.447	48.3	43.9

Table 44. Downstream reservoirs identified in the microcystin regression tree for endpoint three in figure 11.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one; n.a., data not available]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Erosion ratio	TSI(*SD*)	TSI(*CHL*)
City Lake	North Carolina	34.88294508	–79.69233539	0.879	33.0	64.5	57.2
Concord Pond	Delaware	38.64255861	–75.55407739	3.226	42.9	57.3	63.8
Lake Demopolis (2)	Alabama	32.52054008	–87.87913091	1.066	126.6	68.9	53.1
Lake Monroe	Florida	28.83478422	–81.31901778	0.796	33.0	67.8	64.2
Swiggetts Pond	Delaware	38.86893187	–75.37844493	3.640	45.0	n.a.	51.6

Table 45. Downstream reservoirs identified in the microcystin regression tree for endpoint four in figure 11.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Erosion ratio	Basin perma-nence	TSI(*SD*)	TSI(*CHL*)
Falls Lake	North Carolina	35.94103148	–78.58072879	0.918	16.011	0.546	63.6	59.7
Hennington Lake	Mississippi	31.29583249	–89.44115077	0.791	22.322	0.196	55.7	52.9
Holt Lock and Dam (3)	Alabama	33.25401442	–87.44933797	1.056	15.954	0.498	53.2	58.3
Lake Brandt	North Carolina	36.17273048	–79.83855119	1.400	18.966	0.286	66.7	64.0
Lake Townsend	North Carolina	36.18933701	–79.73196512	1.115	17.675	0.331	58.0	55.5
Logan Martin Lake	Alabama	33.42597982	–86.33653698	0.858	17.257	0.395	63.7	64.6
Morris Reservoir (3)	Connecticut	41.67475140	–73.14349713	0.849	15.878	0.525	40.2	41.8
Pachaug Pond	Connecticut	41.58226140	–71.92998840	0.955	16.127	0.577	46.2	40.9
Tuckertown Reservoir	North Carolina	35.48482108	–80.17678299	1.396	16.675	0.446	59.6	66.0

Table 46. Downstream reservoirs identified in the microcystin regression tree for endpoint five in figure 11.

[mg/L, milligrams per liter; TSI(*SD*), Carlson's Trophic State Index for Secchi depth; TSI(*CHL*), Carlson's Trophic State Index for chlorophyll *a*; (#), number of samples if more than one]

Reservoir name	State	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)	Total nitrogen flow-weighted concentration of the inflow load estimate (mg/L)	Erosion ratio	Basin perma-nence	TSI(*SD*)	TSI(*CHL*)
Beaverdam Lake	North Carolina	35.81493621	–78.53290072	1.099	24.0	0.104	67.4	73.9
Coursey Pond	Delaware	38.98879441	–75.51097759	3.318	31.5	0.052	76.2	73.3
Lake Lee (2)	North Carolina	34.96593248	–80.51090979	2.617	28.7	0.061	72.6	75.2
Noxontown Pond (3)	Delaware	39.43391441	–75.68356033	2.278	22.9	0.103	71.7	74.5
Packanack Lake	New Jersey	40.93390807	–74.25638673	2.071	24.3	0.104	68.6	82.4

Validation

The waterbodies in the validation dataset were separated into lakes, headwater reservoirs, and downstream reservoirs. SPARROW nutrient load estimates and morphometrics derived using EPA National Lake Morphometry data were applied to each waterbody. Using the respective regression trees and break points (figs. 3–11), each of the validation waterbodies were placed into their respective endpoint. If an endpoint contained five or more Secchi depths or chlorophyll *a* concentrations, their values were averaged. Secchi depth and chlorophyll *a* trophic state indices (eqs. 7 and 8) were calculated from the mean Secchi depth and chlorophyll *a* concentration within each endpoint. These were plotted (fig. 12) against the respective endpoint Secchi depth and chlorophyll *a* average trophic state values from the study dataset for the three waterbody types (lakes, headwater reservoirs, and downstream reservoirs, figs. 3–11). The resulting regression equation had a y-intercept of 26.969 and a slope of 0.475, with an R^2 of 0.514. Given the limited data pairs to compare against (15 out of a possible 30 endpoints), the ability to evaluate lake and reservoir susceptibility to eutrophication on the basis of SPARROW nutrient load estimates, flushing rate, and waterbody morphometrics appears reasonable.

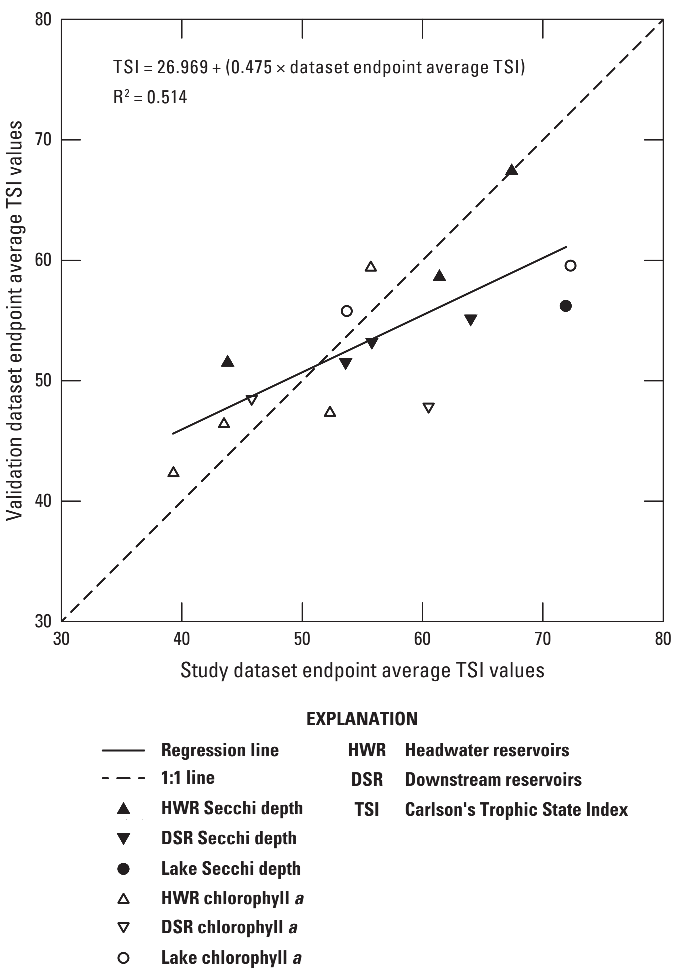


Figure 12. Scatter and regression plot of the trophic state indices determined from mean Secchi depths and chlorophyll *a* concentrations from the study regression tree endpoints and the endpoints from the validation dataset using break point values in the respective regression trees.

Application

A table is provided in the associated data release (Heal and Green, 2021) for this study, listing all waterbodies greater than 0.1 km^2 within the watersheds draining to the Atlantic and Gulf of Mexico coasts and for watersheds in the Tennessee River Basin that have both USGS SPARROW nutrient loading values and EPA National Lake Morphometry data.

The following procedure can be used to examine the susceptibility of a waterbody of interest to eutrophication.

- Select a waterbody of interest from the aforementioned data-release table. Then, using the outlet latitude and longitude information provided, use the online map application to determine if the waterbody is a natural lake, headwater reservoir, or downstream reservoir. In this example, we use Reed Bingham Park Lake, a headwater reservoir in Georgia (fig. 13). The reservoir's outlet latitude is 31.162 and its longitude is −83.543 (table 7). The total nitrogen flow-weighted concentration of the inflow load estimate is 2.641 mg/L, the total phosphorus flow-weighted concentration of the inflow load estimate is 0.158 mg/L, the shoreline development ratio is 2.13, the morphometric factor is 0.087, the development of volume is 1.189, the basin permanence is 0.015, the relative depth is 0.019, and the erosion ratio is 2.93850.

- Using the appropriate Secchi depth (fig. 4), chlorophyll *a* (fig. 7), and microcystin regression trees (fig. 10), identify the endpoint Reed Bingham Park Lake lies within. The expected trophic state based on Secchi depth (fig. 4) given the reservoir's values for basin permanence and relative depth would be eutrophic-hypereutrophic. The expected trophic state based on chlorophyll *a* concentration (fig. 7) given the reservoir's total phosphorus and total nitrogen flow-weighted concentrations of the inflow load estimates would be eutrophic-hypereutrophic. The expected microcystin concentration (fig. 10) based on total nitrogen flow-weighted concentration of the inflow load estimate would be in the range depicted in the boxplot within endpoint five.

- In the online map application, look at the lake or reservoir, as well as the drainage basin upstream, to determine if the predicted Secchi depth, chlorophyll *a*, and microcystin endpoints or positions are valid and

Figure 13. Aerial image of Reed Bingham Park Lake, Georgia.

represent the waterbody's condition. In the example above for Reed Bingham Park Lake (fig. 13), a shallow (filling-in) headwater reservoir located in south-central Georgia within an agricultural intensive watershed, the waterbody is expected to be eutro-hypereutrophic.

- Assess the independent variables (that is, the nodes in the regression tree) that lead to the waterbody of interest to assess what might be driving its water-quality condition. Given that the trophic state of Reed Bingham Park Lake is weighted by low basin permanence (approaching zero) in the case of expected Secchi depth and by high total phosphorus and nitrogen flow-weighted concentrations of the inflow load estimate in the case of expected chlorophyll *a* concentrations, a management strategy to improve water quality might include both establishing total maximum daily loads of both nitrogen and phosphorus within the watershed and dredging the fill material within the reservoir.
- Those lakes and reservoirs that fall within an endpoint that appears to be out of place given the present trophic conditions may presently be in that trophic condition because of influences not captured in the regression trees provided in this report, and therefore further investigation will be needed. For example, 2007 National Lake Assessment records for Reed Bingham Park Lake (U.S. Environmental Protection Agency, 2009) reported Secchi depth at 1.2 m (TSI = 57.4) and chlorophyll *a* at 15.1 µg/L (TSI = 57.2). The TSI threshold between mesotrophic and eutrophic is 50 and between eutrophic and hypereutrophic is 70, indicating that the trophic state of Reed Bingham Park Lake is at the lower end of the eutrophic range. The regression tree output identified the reservoir as eutro-hypereutrophic. Therefore, this example could be a location where water-resource management practices focus on protection, rather than restoration, of water quality. According to the aerial view of the reservoir (fig. 12), the riparian buffer is extensive around the reservoir itself and upstream on both sides of the major inflow tributary. Resource management strategies may consider protecting the Buck Creek riparian zone upstream and the shoreline around Reed Bingham Park Lake to keep the reservoir from progressing further into a hypereutrophic state.

Data Files

All sample data, results, and scripts compiled during this study are available as a USGS data release (Heal and Green, 2021). These data are available in text or .csv (comma separated value) files. The R-scripts provided in the data release include forcing variables not included in this study; they are commented out using the hashtag (#). These additional forcing variables will allow a user to explore other possible relations between the drivers and the responses.

Summary and Conclusions

A combination of U.S. Geological Survey SPARROW (SPAtially-Referenced Regression On Watershed attributes) model nutrient load estimates for lakes and reservoirs, waterbody morphometrics calculated from data in the U.S. Environmental Protection Agency lake morphometry database, and flushing rates were analyzed using regression tree analysis to group waterbodies having similar Secchi depths and concentrations of chlorophyll *a* and microcystin. Groupings were completed for 232 waterbodies greater than 0.1 square kilometer within the watersheds draining to the Atlantic and eastern Gulf of Mexico coasts of the United States, and for watersheds in the Tennessee River Basin (that is, watersheds in the eastern U.S. SPARROW model area) that were included in the U.S. Environmental Protection Agency National Lake Assessment 2007 and 2012 programs. Waterbodies were categorized by type (65 natural lakes; 121 headwater reservoirs; and 46 downstream reservoirs) and assessed independently.

The findings from the regression tree analysis can be used, along with information on flow-weighted mean concentration of nitrogen and phosphorus in inflow loads, flushing rate, and waterbody morphometrics, to identify the associated regression tree endpoints and trophic state for each of the 7,917 lakes and reservoirs in the eastern and southeastern United States with a surface area greater than 0.1 square kilometer. Those lakes and reservoirs that fall within an endpoint that appears to be out of place given the present trophic conditions, may presently be in that trophic condition because of influences not captured in the regression trees provided in this report, and therefore further investigation may be warranted. An application (procedure) is provided to examine the susceptibility of a given waterbody of interest to eutrophication using Reed Bingham Park Lake in Georgia as the example.

Acknowledgments

The authors would like to acknowledge the valuable contributions by U.S. Geological Survey colleague Victor Roland in providing some of the initial R-scripts that initiated this venture, as well as the valuable and thorough peer reviews by U.S. Geological Survey colleagues Jennifer Graham and Amy Gill. All of these efforts allowed for a better product and are worthy of recognition.

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Publishing support provided by
Lafayette Publishing Service Center

USGS

Green and others—**Development of a Screening Tool To Examine Lake and Reservoir Susceptibility to Eutrophication in Selected Watersheds**—SIR 2021–5075

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20215075