

WHICH NUTRIENT CRITERIA SHOULD STATES AND TRIBES CHOOSE TO  
DETERMINE WATERBODY IMPAIRMENT?: USING SCIENCE AND JUDGMENTS  
TO INFORM DECISION MAKING

by

Melissa A. Kenney

Division of Environmental Sciences and Policy  
Duke University

Date: \_\_\_\_\_

Approved:

\_\_\_\_\_  
Kenneth H. Reckhow, Supervisor

\_\_\_\_\_  
Robert T. Clemen

\_\_\_\_\_  
Ralph L. Keeney

\_\_\_\_\_  
Craig A. Stow

Dissertation submitted in partial fulfillment of  
the requirements for the degree of Doctor  
of Philosophy in the Division of Environmental  
Sciences and Policy in the Graduate School  
of Duke University

2007

ABSTRACT

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## **Abstract**

Nutrients are the number one water pollution problem for U.S. lakes, reservoirs, and ponds. Excessive nutrients, such as nitrogen and phosphorus, lead to eutrophication, a condition that can include low oxygen levels, noxious algal blooms, and fish kills. Since eutrophication is a condition that manifests itself differently in different systems, there is not a criterion variable with a clear threshold that can be used to set the criterion level. This dissertation presents an approach to address the question: How should States and Tribes choose nutrient criteria to determine eutrophication-related impairments of the designated use? To address this question I used a combination of water quality modeling and decision analysis to determine the optimal nutrient criterion variables and levels. To choose criterion variables that are predictive of the designated use, I utilized statistical models (structural equation models, multiple regression, and binomial regression model) to link the measured water quality variables to expert elicited categories of eutrophication and the designated uses. These models were applied successfully to single waterbodies, the Kissimmee Chain-of-Lakes region, and the State of North Carolina to assess which candidate criterion variables were the most predictive. Additionally, the models indicated that the variables that were most predictive of eutrophication were also the most predictive of the designated use. Using the predictive nutrient criteria variables, I applied a decision-analytic approach to nutrient criteria setting in North Carolina. I developed a nutrient criteria value model

that included two submodels, a water quality model and a multiattribute value model. The submodels were parameterized using a combination of water quality data, expert elicitation data, and utility assessments. The outcome of the nutrient criteria value model is the overall expected value for a criterion level choice; the optimal criterion level would be the choice that maximized the expected value. Using the preferences of North Carolina environmental decision-makers and a total phosphorus criterion variable, the optimal criterion level was between 0.03 mg/L and 0.07 mg/L. Ultimately, I hope this research will establish methodology used to set appropriate water quality criteria.

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# **1. Introduction**

## ***1.1 Clean Water Act and Water Quality Standards***

The Federal Water Pollution Control Act, or Clean Water Act (CWA), governs pollution of the United States of America (U.S.) surface waters. Though this act was originally enacted in 1948, the 1972 and 1977 amendments significantly increased the law through programs and enforcement mechanisms designed “to restore and maintain the chemical, physical, and biological integrity of the nation’s waters (Section 101).” There were additional amendments to the CWA in 1981 and 1987 (Copeland 2002).

To attain fishable and swimmable waters, the CWA utilizes water quality standards (Section 303). Instead of developing federally-mandated standards, an interesting feature of the law is that it creates a federal-state partnership where the agenda is set by the federal government, but the state governments set the water quality standards, monitor the waters, and implement and enforce pollution mitigation assignments and activities (Copeland 2002). The federal government, through the U.S. Environmental Protection Agency (USEPA), retains oversight of the states to assure that they are adequately setting water quality standards and carrying-out the day-to-day activities required to evaluate the waters and, when necessary, enforce pollution reductions (Copeland 2002).

The method to set water quality standards is chosen by the state, but all standards comprise three basic elements: an antidegradation clause, a qualitative designated use, and a qualitative or quantitative criterion. The antidegradation clause is a narrative statement that the designated use cannot be demoted because of degraded water quality conditions. The designated use is a narrative statement that describes the existing and potential water quality goal, such as fishable and swimmable. The criterion is a numeric measure or narrative statement that serves as a scientific surrogate for the designated use; the criterion is a combination of a water quality variable and the criterion level for that variable. Another element in a water quality standard is the general policies, which address implementation issues such as low flows and mixing zones.

Ideally, we would directly assess attainment of the designated uses. But since there is not an easy, straightforward method to assess whether a designated use goal, such as water propagation of fish, shellfish, and wildlife is attained, we use easily measurable water quality variables, or criteria, to serve as a proxy for pollution-related designated use impairments.

Since we assess the impairments to the designate uses in respect to a particular pollutant or source of pollution, it is essential to find criterion variables that are easily measurable and good indicators of both the source of pollution and the designated uses. For certain pollutants, such as metals, the criterion variable choice is obvious and the selection of the level is made easier by clear environmental thresholds. When

impairments are the result of a condition, such as eutrophication, that cannot be directly assessed and is indicated by multiple variables, it is more difficult to set water quality criteria.

## **1.2 Eutrophication**

The USEPA proclaimed nutrients to be the number one cause of water quality pollution for lakes, reservoirs, and ponds, causing the eutrophication of 3.8 million acres of waters (Environmental Protection Agency 2002). Eutrophication is a condition fueled by excess nutrients, such as nitrogen and phosphorus, which can lead to undesirable outcomes such as anoxia, noxious algal blooms, and fish kills (Novotny and Olem 1994, Chapra 1997). Eutrophication is a natural process where an increase of nutrients over many centuries can cause a waterbody to change from oligotrophic to eutrophic to wetlands to dry land (Novotny and Olem 1994, Chapra 1997). As a society we are most concerned with anthropogenic, or cultural, eutrophication where waters are overenriched as a result of human activities.

Though eutrophication can occur in a range of waterbody types, my dissertation focuses on eutrophication impairments of lakes and reservoirs because the designated uses of these waterbodies are impacted by eutrophication more than any other source of impairment. Natural lakes and man-made reservoirs are similar in many ways; however, there are some important differences. Reservoirs are more prevalent in areas where there are few natural lakes; therefore, states like Minnesota have few reservoirs

because that state is dominated by natural lakes where states like Virginia are dominated by reservoirs because there are few natural lakes. Reservoirs tend to have higher annual load inputs of nitrogen and phosphorus, but the chlorophyll a response is much less per unit nutrient than in natural lakes (Cooke and Carlson 1989).

Despite the lower algal response, as measured by chlorophyll a, the mean daily productivity ( $\text{mg C m}^{-2} \text{ day}^{-1}$ ) is generally greater in reservoirs than in natural lakes (Kimmel et al. 1990). The higher productivity levels directly impact the trophic status, with more reservoirs than natural lakes considered mesotrophic or eutrophic (Kimmel et al. 1990). Since there are several important distinctions between lakes and reservoirs, particularly in regards to eutrophication, in this dissertation, I will make the distinction between natural lakes, referred to as lakes, and man-made reservoirs, referred to as reservoirs.

Since eutrophication is a condition that manifests itself differently in different systems and across systems, there is not a single measured water quality variable that is a perfect indicator of trophic status. Despite this fact, there still needs to be a way to set criteria to protect for eutrophication-related designated use impairments. As a result, the USEPA is encouraging States and Tribes to identify and combat eutrophication impairments.

### **1.3 Nutrient Criteria**

Nutrients, such as nitrogen and phosphorus, themselves do not typically interfere with the designated uses; however, the input of nutrients affects the in-lake biological response. This biological response, in excess, can cause eutrophication problems that interfere with designated use attainment (Walker et al. 2007). To combat eutrophication-related designated use impairments, many States and Tribes have had narrative or less commonly numeric nutrient criteria; these criteria have been used to identify 10,000 nutrient impaired waters (Grumbles 2007). In an effort to promote numeric nutrient criteria, the USEPA has developed the national nutrient strategy.

The national nutrient strategy (Grubbs 2001) sets an agenda to encourage States and Tribes to adopt numeric nutrient criteria translators or numeric nutrient criteria, both referred to as nutrient criteria henceforth. By nutrient criteria, USEPA means any measurable water quality variable or variables that can be used to detect eutrophication impairments (i.e. phosphorous, algae, water clarity, etc.) and their associated criterion levels. The adoption of these nutrient criteria are expected to steer water quality assessment, support TMDL development, and focus watershed protection plans (Grumbles 2007). As a result, many States and Tribes are asking: Which nutrient criteria should they choose? There is not a best answer, which has lead to much debate about what method should be used to establish these standards.

## **1.4 Nutrient Criteria Selection Methods**

The method used to set nutrient criteria is left to the best judgment of the state. However, the basic structure of the nutrient criteria decision includes three primary decisions: (1) how to classify the waterbodies, (2) how to choose the criterion variable(s), and (3) how to choose the criterion level(s). The USEPA and several States have developed methods to establish nutrient criteria, using a variety of techniques; I will present a number of these approaches in detail.

### **1.4.1 USEPA's Ecoregion Reference Waterbody Approach to Nutrient Criteria**

The USEPA-endorsed nutrient criteria guidance is an ecoregion approach using a reference waterbody strategy (Environmental Protection Agency 2000b, a, e, 2001). Using the USEPA approach, the U.S. is subsectioned into 14 ecoregions (Level III), which represent areas of the country with similar geology, soils, hydrology, climate, vegetation, and wildlife (Omernik and Bailey 1997, Griffith et al. 2002). The method also subsections based on the waterbody type, breaking up the classification into streams and rivers, wetlands, estuarine and coastal waters, and lakes and reservoirs. Focusing on lakes and reservoirs, the guidance does not distinguish between natural lakes and man-made reservoirs.

The USEPA method recommends setting criteria based on the reference conditions for the lakes and reservoirs in the given ecoregion (Environmental Protection

Agency 2000e). Reference conditions are waters that represent pristine or minimally impacted conditions. These reference conditions, USEPA argues, should be used to set the upper bounds, given an ecoregion, to maintain or achieve natural and attainable conditions for lakes and reservoirs (Environmental Protection Agency 2000a, b, 2001).

Since USEPA wished to develop nutrient criteria that reflected both the causal and the response conditions of eutrophication, they recommended using four variables: total phosphorus, total nitrogen, chlorophyll a, and Secchi depth. In the USEPA guidance, there was no weight of more importance given to one variable versus another variable.

To set the criterion levels, the marginal distribution of each variable was used instead of the joint distribution of the variables. The criterion levels were set for each ecoregion by developing seasonal (winter, spring, summer, and fall) frequency distributions using all lakes and reservoirs within an ecoregion. Each criterion variable was ordered. For total phosphorus, total nitrogen, and chlorophyll a, the data was ordered from low values to high value; for Secchi depth, the values were ordered from high values to low values. The 25<sup>th</sup> percentile of each of the four seasons was calculated; the median value of these 25<sup>th</sup> percentiles was used to set the criterion level (Walker et al. 2007).

The USEPA chooses to use the 25<sup>th</sup> percentile of these distributions because it approximates the 75<sup>th</sup> percentile of the distribution of reference waterbodies. USEPA argues that using the reference conditions to set nutrient criteria "...will be protective of

the designated uses, and provides management flexibility (Environmental Protection Agency 2000b, a, 2001).” Therefore, the criterion is not directly connected to the designated use, lacking a substantive justification for the criterion variables and levels.

It is important to note that most watersheds have multiple land uses, designated uses, and human influences, which makes the choice of a reference waterbody difficult to impossible. The idea of using minimally impacted waters is further criticized when considering states, such as North Carolina, that are dominated by non-natural, man-made reservoirs.

Additionally, the use of a 25th percentile of the distribution of all waterbodies or 75th percentile of the distribution for reference waterbodies is a largely arbitrary judgment, which is often misinterpreted as a strict scientific cutoff point. Therefore, the ecoregion reference waterbody approach is a method to set criteria and threshold levels that uses both scientific knowledge and statistical analysis, but it does not explicitly connect to the designated use (Environmental Protection Agency 2000b, a, 2001).

#### **1.4.2 Minnesota’s Nutrient Criteria Approach**

The approach that Minnesota is using the set nutrient criteria is heavily influenced by the USEPA ecoregion reference waterbody method and their previous total phosphorus criterion (Heiskary and Wilson 2005). Similar to the USEPA method, Minnesota classified their lakes and reservoirs by ecoregion and reference conditions. They additionally subset the waters via natural lakes versus reservoirs, designated uses,

and depth (Walker et al. 2007). Minnesota has few reservoirs, therefore the criteria were developed for natural lakes; site-specific criteria were developed for the reservoirs (Heiskary and Wilson 2005). Since the lakes have multiple designated uses, the most sensitive designated use, per depth category, was the designated use protected. It was assumed that if the most sensitive use is managed, the other uses are appropriately protected. Finally the lakes were classified as deep or shallow waters; shallow lakes were depths less than 15 feet and deep lakes were greater than 15 feet (Walker et al. 2007).

After the waters were classified, then criteria were developed for each of the classifications. Instead of using a single criterion, such as the current total phosphorus criterion set in 1988, Minnesota has chosen to develop criteria using three criterion variables, total phosphorus, chlorophyll a, and Secchi depth. Minnesota did not include nitrogen since their waters are phosphorus limited. Additionally, they chose to add two response variables, at the suggestion of USEPA's guidance, public and user perceptions, and scientific literature. These response variables are also highly correlated with total phosphorus.

The criterion levels were set using a weight-of-evidence approach that employed a variety of methods such as the Carlson's Trophic State Index, historical studies of in-lake phosphorus, user perceptions, requirements by aquatic life, 75<sup>th</sup> percentiles of reference lakes, 25<sup>th</sup> and 50<sup>th</sup> percentiles of all lakes, and relationships between total phosphorus and chlorophyll a or Secchi depth. The levels for total phosphorus,

chlorophyll a, and Secchi depth were different for the different classifications; however, to exceed the criteria, both total phosphorus and one of the response variables must be exceeded.

Minnesota's method uses the wealth of scientific knowledge regarding eutrophication in Minnesota lakes to refine their current nutrient criterion. The selection of the criterion variable, though it is meant to protect the designated use, has not been explicitly linked to the specific designated uses. Additionally, the choice of the criterion levels is devoid of the inherent trade-offs underlying this policy decision.

### **1.4.3 Virginia's Adaptive Approach to Nutrient Criteria**

Virginia is taking an adaptive approach to assessing eutrophication impairments to lakes and reservoirs (Walker et al. 2007). First, the lakes and reservoirs are classified based on their ecoregion, waterbody category, and type of recreational fishery. In an effort to create nutrient criteria that are protective of the designated uses, Virginia chose to set nutrient criteria for a designated use that applies to all their lakes and reservoirs, recreational fishing (Walker et al. 2007). Virginia chose to use recreational fisheries because they felt that developing criteria protective of the fishery would also protect the other designated uses.

To assess designated use attainment, Virginia felt that the ideal indicator would be the population status of sport fish species because these species are the top predators and depend on the survival of lower level aquatic life for their survival. Since a census

of fish populations is not an easily measurable variable, they chose to use total phosphorus and chlorophyll a, given the recommendations of a panel of experts, as their nutrient criteria variables (Walker et al. 2007).

Virginia decided to use a nutrient criterion of chlorophyll a, except when algecides are applied to the reservoir to control for algal growth; then total phosphorus is the nutrient criterion. For both of these criteria variables, the levels were set using best professional judgment given literature values to sustain various recreational fisheries.

Virginia, unlike other states, has set up a two-step process to classify designated use impairment. First, assessments are conducted to determine if the reservoir exceeds the nutrient criterion. Then, if the waterbody is exceeding the criterion, additional research is conducted at the site to assess the status of the designated use. If the assessment reveals that the designated use is unimpaired, even though the criterion is exceeded, then site-specific criteria are proposed (Walker et al. 2007) and the waterbody is not classified as impaired.

#### **1.4.4 Arizona's Translator Approach to Nutrient Criteria**

Arizona is using a "translator" approach to translate the State's narrative nutrient criteria into numeric nutrient criteria equivalent (Walker et al. 2007). The Arizona lakes and reservoirs are first classified by their designated uses and lake class. Using a classification and regression tree (CART) model, they were able to subsection

their waters into useful groups. Then, Arizona used a weight-of-evidence approach to compare monitoring data to targets provided by sources such as scientific literature, the trophic state index developed for Arizona waters, and statistical analysis (Walker et al. 2007). Using this information a chlorophyll a criterion was recommended, with secondary consideration to Secchi depth, total phosphorus, total nitrogen, and total Kjeldahl nitrogen. The targets for the secondary nutrient criterion variables were developed through their correlation with chlorophyll a (Walker et al. 2007). A waterbody would be classified as impaired if there were two exceedances of the nutrient criteria within a 2-5 year assessment period.

#### **1.4.5 North Carolina's Expert Panel Approach to Nutrient Criteria**

North Carolina, unlike most other states, has had numeric nutrient criteria since 1979. The state uses a criterion of chlorophyll a with a threshold level of 40 ug/L for warm water and 15 ug/L for cold water for Class C waters (secondary contact recreation, fishing, and aquatic life support) (North Carolina Administrative Code 2003). This criterion was established using a combination of eutrophication literature and the selection of the appropriate transition level by a panel of experts. This method of criterion selection is similar to the method used by other states, which is a mixture of science-based assessment and expert judgment. One of its flaws, similar to the USEPA method, is the lack of a direct link to the designated use and the explicit incorporation of expert judgment.

#### **1.4.6 Critique of Nutrient Criteria Approaches**

States and Tribes may choose any method to establish nutrient criteria as long as it is scientifically defensible and protective of the designated uses (Grumbles 2007). We cannot delay in acting to reduce environmental degradation, but good standard setting is the foundation for assessing whether or not a waterbody is classified as impaired. The standards also resolve, if a waterbody is considered degraded, the amount of pollution reduction needed for improvement. As a result, setting nutrient criteria that are truly predictive of eutrophication-related designated use impairments is essential to properly identify, improve, and restore the desired uses of our waters.

As previously discussed, eutrophication impairments are particularly difficult to identify using generic nutrient criteria since the candidate criteria variables, total nitrogen, total phosphorus, chlorophyll a, and transparency, all occur as part of the natural system at a range of levels. As a result, a number of States and Tribes do not identify strong interrelationships between the causal and response variables (Smithee 2007). Therefore, adopting nutrient criteria that use all four variables, as USEPA promotes, may not be appropriate for many States. Additionally, there must be a substantive linkage between the nutrient criterion and the designated use; the USEPA provides little evidence that the proposed percentile criteria levels for these four variables are predictive and protective of the designated uses.

In contrast to the USEPA, several States have more thoughtfully considered the designated uses in their criteria setting through the use of expert panels or best

professional judgment. None of these methods, however, statistically link the nutrient criteria variables to the designated use. Though explicitly considering the designated uses is essential, I believe that this step is better accomplished by using statistical models to identify criterion variables and to quantitatively assess whether one variable or multiple variables will better predict eutrophication-related designated use impairments.

In addition to appropriately choosing criterion variables, determining reasonable criterion levels is essential to minimize the likelihood of misidentifying waterbodies. As discussed, as part of a natural, diverse system, our nation's waters are at various successional stages. Since the candidate criterion variables are a natural part of our waters, these variables do not exhibit traditional threshold effects, and therefore, threshold methods, which previously dominated criteria setting, are not appropriate to set criterion levels (Smithee 2007).

The modified approach used by USEPA to set statistically-derived "threshold" levels is not scientifically defensible. First, there is no scientific justification for the threshold levels using either an eutrophication or a designated use argument. Second, USEPA does not explicitly consider the interrelationship between the causal and response variables when setting the criterion levels. Last, their approach fails to distinguish between science and judgments, making the implicit risk-based decision incorporated to set the criterion levels seem scientifically driven rather than the combination of science and judgment (Reckhow et al. 2005).

Given the importance of setting appropriate criterion variables and levels to determine impairment, one of the most troubling aspects of the USEPA approach is that the criteria may be overprotective or underprotective. Either result would be disastrous because overprotective criteria would needlessly waste scarce resources and underprotective criteria would not properly identify degraded systems (Smithee 2007).

Therefore, I believe that there is a better method to approach setting criterion levels. Setting criterion levels is a policy decision, in which science is only one part. Setting criteria inherently involves making trade-offs between maximizing environmental protection and minimizing costs. These trade-offs should be made explicit. To assist in transparently breaking-down a complex decision such as this, I believe it is essential to use quantitative decision support tools that are parameterized with the decision-makers' preferences and trade-offs. These tools provide a means to clearly separate the science and judgments while providing concrete recommendations for nutrient criterion levels.

### ***1.5 Dissertation Objectives***

The objective of my dissertation is to address the question: How should States and Tribes choose nutrient criteria to determine eutrophication-related impairments of the designated use? To address this question I used a combination of water quality modeling and decision analysis to determine the optimal nutrient criterion variables and levels. To choose criterion variables that are predictive of the designated use, I used

statistical models to link the water quality variables to eutrophication and the designated uses. These methods were developed for two single waterbodies, Lake Washington and the Neuse River estuary (Chapters 2), the Kissimmee Chain-of-Lakes region in Florida (Chapter 3), and multiple regions of lakes and reservoirs within the State of North Carolina (Chapter 4). Then, using the predictive nutrient criteria variables, I applied a decision-analytic approach to nutrient criteria setting in North Carolina to recommend criterion levels that maximize the decision-makers' expected value (Chapter 5). Finally, I summarize the methods and results and offer suggestions for future research directions (Chapter 6). In the dissertation I use several case studies to illustrate my approach to nutrient criteria development; however, the method could be applied to any type of waterbody in any region of the United States.

## **2. A Predictive Approach to Nutrient Criteria**

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### **2.1 Introduction**

Violation of a water quality standard triggers the need for a Total Maximum Daily Load (TMDL); this should result in actions that improve water quality, but sometimes at significant cost. If the standard is well-conceived, a designated use statement characterizes societal values, and a criterion provides a measurable surrogate for designated use. This latter provision means that scientists measure the criterion and view exceedances of the criterion as equivalent to noncompliance with the designated use. However, if a criterion is not a good indicator of designated use, it is apt to result in misallocation of the limited resources for water quality improvement through the TMDL process. This concern provides the basis for our assessment of the national nutrient criteria strategy recently proposed by U.S. Environmental Protection Agency (USEPA). We acquired water quality data sets and then used expert elicitation to quantify designated use attainment for each case. Applying structural equation modeling, we identified good water quality criteria as the best predictors of the designated use elicited

response variable. Further, we used the model to relate the level (concentration) of each criterion to the probability of compliance with the designated use; this provides decision makers with an estimate of risk associated with the criterion level, facilitating the selection of appropriate water quality criteria. This approach was applied to a single waterbody, a region of waterbodies, and the state of North Carolina.

## **2.2 Background**

The U.S. Environmental Protection Agency (USEPA) recently recommended an ecoregion-based national strategy for establishing nutrient criteria, following a multi-year study of needs and approaches (Environmental Protection Agency 2000e). The importance of nutrient criteria is evident from the Clean Water Act's required listing of impaired waters under Section 303(d); state water quality standard violations due to nutrient over-enrichment are a leading cause of surface water impairment (Environmental Protection Agency 2000d). Clearly, a sound scientific basis is needed for the many costly Total Maximum Daily Loads (TMDLs) that will be required.

Eutrophication-related water quality standards and criteria already widely exist. For example, most states have dissolved oxygen criteria intended to be protective of designated uses that are impacted by oxygen depletion resulting from nutrient-enhanced algal production. Additionally, some states have adopted nutrient or chlorophyll criteria; for example, North Carolina has a chlorophyll *a* criterion of 40 µg/L. However, criteria like the North Carolina chlorophyll criterion were set years ago using

informal judgment-based determinations; USEPA's new strategy reflects a recognition that more analytic rigor is needed given the consequences of TMDL decisions.

State water quality standards are established in accordance with Section 303(c) of the Clean Water Act and must include a designated use statement and one or more water quality criteria. The criteria serve as measurable surrogates for the narrative designated use; in other words, measurement of the criteria provides an indication of attainment of the designated use. Additionally, exceedance of the criteria is a basis for regulatory enforcement, which typically requires establishment of a Total Maximum Daily Load (TMDL). Thus, good criteria should be easily measurable and good predictors of the attainment of designated use.

This latter basis for criteria selection – that they must be good predictors of the attainment of designated use – is the motivation for our study. We believe that the best criterion for eutrophication-related designated use is a measurable water quality characteristic that is also the best designated use predictor. In addition, we believe that there are alternative and arguably better ways to define the criterion level than through reference to least impacted waterbodies expected to be in attainment of designated use. Rather, because it is an enforceable surrogate for designated use attainment, the level of the criterion should be chosen based on societal values, which should reflect the realities of society's trade-offs between environmental protection and cost (Barnett and O'Hagan 1997). Beyond that, selection of the level of the criterion should realistically take into consideration natural variability and uncertainty in predicting water quality outcomes,

both of which imply that 100% attainment in space/time is not a realistic basis for a standard.

Our objective is to describe and demonstrate the application of a prediction based procedure for nutrient criteria selection. The procedure involves application of structural equation modeling (SEM) (Bollen 1989, Kline 1998) to data from individual lakes, rivers, and estuaries to assess predictive relationships among candidate water quality criteria. It also involves expert elicitation to quantify the narrative designated use for each waterbody and to identify the conditions for use attainment (Expert elicitation) (Morgan and Henrion 1990, Meyer and Booker 1991). Combining the elicited judgments with the water quality data, we create a data set that allows us to use SEM to identify the best predictive criterion for designated use. In addition, we can use the resultant structural equation model to estimate the probability of attainment associated with various levels of the criterion.

In the next section, we discuss the traditional approaches to water quality standard setting, the national nutrient criteria strategy recently proposed by USEPA, and our prediction based approach for nutrient criteria selection. Following that, we describe two key methods – expert elicitation and structural equation modeling – used in our work, and demonstrate our approach using two case studies. The paper concludes with a discussion comparing strategies for nutrient criteria selection and a list of modifications for improving our approach.

### **2.2.1 Water Quality Standards and Nutrient Criteria**

Designated uses evolved from the goals of the Clean Water Act. As part of the water quality standard for a regulated waterbody, they are typically expressed as brief narrative statements listing the uses that the waterbody is intended to support, such as drinking water, contact recreation, and aquatic life. Water quality criteria must then be chosen as measurable quantities that provide an indication of attainment of the designated use. Finally a criterion level (and possibly the frequency and duration) must be selected as the cutoff point for nonattainment.

Traditionally, the task of setting criteria has involved judgments by government and university scientists concerning the selection of specific water quality characteristics, and the levels of those characteristics, that are associated with the designated use. For example, consider the North Carolina chlorophyll *a* criterion of 40 µg/L, which was established in 1979. This criterion applies to Class C waters, which are freshwaters with use designations of secondary recreation, fishing, and aquatic life support (North Carolina Administrative Code 2003). To establish this criterion, the NC Division of Environmental Management examined the scientific literature on eutrophication, and then recommended a chlorophyll criterion level of 50 µg/L to a panel of scientists for consideration. After reviewing a study of nutrient enrichment in 69 North Carolina Lakes (Weiss and Kuenzler 2001), the panel responded that 40 µg/L reflected a transition to algal, macrophyte, and DO problems and thus represented a better choice. Following

public hearings, 40 µg/L was adopted (Gray 2001). Thus, the 40 µg/L criterion developed from an ad hoc process of science-based expert judgment.

The current USEPA approach for nutrient criteria development is a similar mix of science and expert-judgment. In 1998, the President's Clean Water Action Plan directed USEPA to develop a national strategy for establishing nutrient criteria. The resultant multi-year study produced a set of documents (Environmental Protection Agency 2000e) and recommended criteria based on ecoregions and waterbody type. Specific modeling methodologies were proposed to aid in the extrapolation of reference conditions and to assist managers in setting loading allowances once nutrient criteria have been established. In addition, enforcement levels for the proposed criteria were based on "reference waterbodies" perceived to reflect essentially un-impacted conditions.

In principle, standard setting should be viewed from the perspective of decision making under uncertainty, involving interplay between science and public opinion. The determination of designated uses reflects public values, both in the statements in the Clean Water Act and in the waterbody-specific statement of designated use. The selection of the criterion is a choice based largely on science. Selection of a good criterion, one that is easily and reliably measured and is a good indicator of designated use, is largely a scientific determination.

However, determination of the level of the criterion associated with the attainment-nonattainment transition ideally requires the integration of science and

values. Natural variability and scientific uncertainty in the relationship between the criterion and the designated use imply that selection of a criterion level with 100% assurance of use attainment is generally unrealistic. Accordingly, scientific uncertainty and attitude toward risk of nonattainment should be part of the criterion level decision. Therefore, the decision on criterion level might be addressed by answering the following question: Acknowledging that 100% attainment is impractical for most criteria, what probability (or, perhaps, what percentage of space-time) of nonattainment is acceptable? USEPA guidance (Environmental Protection Agency 1997) addresses this question by suggesting that 10% of samples may violate a criterion before a waterbody is listed as not fully supporting the designated use. Analytically, this question may be answered by integrating the probability of use attainment (for a given criterion level) and a utility function reflecting water quality costs and benefits. The criterion level associated with the highest expected utility might then be chosen. Realistically, this decision analytic framework is prescriptive; it guides us toward what ought to be done, but it almost certainly exceeds what actually will be done.

Both the traditional approach and the current USEPA approach to standard setting contributed in an important way to our proposed strategy. The traditional approach, as reflected in the NC chlorophyll *a* example, illustrates the importance of expert judgment concerning the relationship between criteria and designated uses. Yet, as we reviewed Gray's (2001) description of the process, we recognized the shortcomings of a single, albeit thoughtful, informal group consensus on chlorophyll *a*

levels associated with higher-level biological transition points. Thus, while we saw the need for expert judgment, we believed that it should be more rigorously elicited and incorporated into the standard setting process.

The USEPA approach is analytically thorough and rigorous, involving data analysis, modeling, and expert judgment. It also uses the reference condition as the norm for standard setting. As described below, our approach has much in common with portions of the analysis recommended by USEPA, while avoiding the value judgment implied in the reference condition. Given the decision analytic perspective presented above, we opted to predict probability of use attainment as a function of criterion level, and leave the choice of criterion level to policy makers. This led to the following approach:

1. We first selected four waterbodies (the Neuse Estuary, San Francisco Bay, Lake Washington, and Lake Mendota) to test our procedure and present two of the analyses here as case studies. These data sets were chosen because they were large; they consisted of many concurrent measurements (taken at numerous locations over several years) of likely criteria (e.g., phosphorus, nitrogen, chlorophyll *a*, and Secchi depth) related to nutrients.
2. For each waterbody, we identified the designated use statements reflecting conditions impacted by nutrient enrichment.
3. Through a carefully choreographed series of interviews with state and university scientists familiar with each waterbody, we used formal procedures of expert

elicitation (Morgan and Henrion 1990, Keeney and von Winerfeldt 1991, Meyer and Booker 2001) to:

- a. re-express designated use in terms of measured waterbody conditions,
  - b. formulate a conceptual model of the variables which affect the designated use, and
  - c. estimate the probability of attainment of the (translated) designated use as a function of actual observations in the data sets.
4. The elicited probability of attainment was added as a new response variable to each of the data sets. Then, for each waterbody, we evaluated structural equation models to determine which criterion(ia) is (are) most predictive of the use attainment.
  5. Finally, we applied the best-fit structural equation model to estimate probability of use attainment associated with the level of the criterion.

The elicitation tasks are controversial yet essential; in the discussion section below, we consider alternatives, such as a user survey applied concurrently with water quality sampling. First, however, we discuss the technique of expert elicitation.

### **2.3 Methods**

While a number of the methods employed in our study are well-understood in environmental science and engineering disciplines, expert elicitation and structural

equation models may be less familiar. Accordingly, we briefly describe these techniques and the rationale for their use here.

### **2.3.1 Expert Elicitation**

We tend to think of science as objective, although it is exceedingly rare that subjectivity can be entirely avoided. In fact, judgment is typically necessary throughout a scientific study – from the statement of hypotheses, the specification of a model, the design of experiments or monitoring programs, the selection of methods of analysis, to the final inferences and conclusions – all of these tasks generally involve expert judgment intermingled with the objective analysis of data (Press and Tanur 2001). Therefore, a realistic appraisal of science must acknowledge a role for the expert judgment of scientists.

Scientists routinely make these judgmental assessments throughout their studies in a thoughtful but informal way. For example, water quality modelers may select the specification of a phytoplankton growth model as a multiplicative function of nitrogen and phosphorus Michaelis-Menten factors, even while recognizing that: (i) other nutrients also may be important, and (ii) a limiting nutrient functional form is a plausible alternative. The true growth dynamics are exceedingly complex; the selected model is a pragmatic judgmental choice made by scientists experienced in phytoplankton growth kinetics.

With this perspective in mind, consider the approaches for the selection of water quality standards and criteria presented in the previous section. Certainly the 1970's strategy involving scientific consensus was heavily judgmental. And, while drawing upon objective statistical analyses, the proposed USEPA national nutrient criteria development strategy still depends on scientific judgment in the selection of reference conditions. Similarly, our proposed procedure incorporates expert judgment as described above. The need to link measured criteria with narrative designated use statements unavoidably requires expert judgment.

So, if any strategy employed for nutrient standard setting will have a judgmental component, how best do we elicit and incorporate expert judgment? Fortunately, there is a good answer to that question, as there exists a vast literature describing methods for judgmental elicitation.

The goal of expert elicitation is to extract subjective judgments from experts in a systematic procedure. This rigorous, transparent process is frequently used in the decision sciences (Morgan and Henrion 1990, Keeney and von Winerfeldt 1991, Meyer and Booker 1991) because it provides a defensible, well-established method for providing necessary information that was informally provided previously. This method of judgmental assessment has been used in the environmental and aquatic sciences also, although to a lesser extent (Reckhow 1988a, Anderson 2001, Borsuk et al. 2002a). The improvement resulting from the use of expert elicitation is that it makes these subjective judgments transparent.

The elicitation method used in this study was developed based on suggestions from the expert elicitation literature (Morgan and Henrion 1990, Keeney and von Winerfeldt 1991, Meyer and Booker 1991, Borsuk 2004). Since there is not a single “cookbook” procedure to obtain expert judgment, each expert elicitation procedure differs because of the expert, judgments to be assessed, and project goals. There is, however, a set of adaptive guidelines to assure that our method would provide us with the best data set possible.

We conducted the elicitation in two stages. The goal of the first stage was to translate the narrative designated use into a quantifiable criterion. In this stage, we interviewed a state scientist or an academic who was familiar with the waterbody and its designated uses. These experts were identified through professional contacts, and they were contacted about voluntary participation in the study. They were told that they were under no obligation to participate and that if at any time they became uncomfortable in providing their judgment and would prefer not to answer the questions, that they could remove themselves from participation in the interview.

Given willingness-to-participate, we contacted each expert via email and provided him with a description of the project and the reason his judgment was necessary. Additionally, the email included a questionnaire to determine which nutrient-related designated use he was most comfortable addressing (there are multiple designated uses for almost all waterbodies) and what qualities (i.e. clarity, free of algal scums, lack of odor) were essential, in his opinion, to maintain the integrity of that

designated use. The expert's responses were used to guide a phone interview in which he was asked to translate these qualities into water quality parameters available in the data set for the waterbody. He was also asked to provide a conceptual model of the factors affecting the attainment of designated use. Thus, the result of the phone interviews was a set of variables to consider when assessing designated use attainment, and a conceptual model of how these variables would affect the attainment of designation use.

In the second stage of the study, an aquatic scientist was provided with the designated use under consideration and the variables identified by the first expert. The aquatic scientist was then presented with a data matrix consisting of fifty multivariate water quality observations taken from the waterbody. He was then asked to provide a probability of attainment for each data row of the matrix. Each row contained the variables identified by the first expert and some others. In addition, each row was complete (i.e. contained no missing values), collected at the same location and time, and the original measurements were not altered. The choice of observations to include was made based on the goal of using the largest range of conditions possible.

The motivation for providing the second expert a set of fifty observations was to solicit values for the probability of designated use attainment given the underlying correlation structure of the water quality data in that waterbody. To assist the water quality expert, we asked the expert to look at each data row individually, considering all of the variables, and answer the question: "Given 100 hypothetical waterbodies in this

State, all with identical summer average levels of these variables and assuming other factors (e.g., morphological, climatic) vary randomly, how many of the 100 waterbodies would be in attainment of the given designated use?" The 100 waterbodies were used as an image to assist the expert, since the majority of people have difficulty thinking in probabilities (Morgan and Henrion 1990, Meyer and Booker 1991). To additionally minimize human error due to heuristics, we conducted a consistency check on the response variable value provided by the expert to assure consistency within their responses and that the experts were not anchoring their responses on the current state standard (Keeney and von Winerfeldt 1991, Meyer and Booker 1991). This value was directly translated to a probability (i.e. 50 waterbodies = 0.50 probability of compliance). These values provided the data necessary to use structural equation modeling to determine which criteria are most predictive of use attainment. (See Appendix A for additional details on the expert elicitation protocol.)

### **2.3.2 Structural Equation Modeling**

Structural equation modeling (SEM) was used for the identification of the relationships between the selected environmental variables and the elicited "probability of attainment of the designated use". SEM has been used in a range of research areas such as social science, chemistry and biology (Joreskog 1981, Bollen 1989, Hayduk 1996, Kline 1998), but ecological applications are still relatively limited and even less common in aquatic ecosystems (Grace and Pugesek 1997, Malaeb et al. 2000, Stow and Borsuk

2003). SEM provides a powerful method for studying the network of relationships among a set of correlated variables. Unlike multivariate regression, this technique allows for explicitly testing indirect effects between two explanatory variables, where the effects can be mediated by another intermediary variable (Bollen 1989, Kline 1998) (e.g., phosphorus concentrations can have an indirect effect on zooplankton through their impact on phytoplankton growth). Another advantage of structural equation modeling is that it can explicitly incorporate error variance due to measurement error or lack of validity of the observed variables (Malaeb et al. 2000). The latter aspect refers to the ability to represent variables or concepts that are not directly measured, by using multiple indicator (observed) variables. For example, in aquatic ecosystems, phytoplankton can be modeled as a common factor of several indicators such as photosynthetic pigments (chlorophyll *a*), primary productivity, algal biovolume or carbon biomass, which individually are imperfect surrogates of the latent variable, phytoplankton.

SEM is an “a priori” statistical technique, where pre-conceptualizations that reflect existing knowledge of the system structure or investigated research questions form the initial framework for model development. The hypothesized model (expected covariance structure) is tested against the covariance matrix from the actual data. The fundamental null hypothesis  $H_0$  that formalizes the basic idea of structural equation modeling is:

$$H_0: \Sigma = \Sigma(\theta) \tag{1}$$

where  $\Sigma$  is the population (or sample) covariance matrix of observed variables,  $\theta$  is a vector that contains the model parameters and  $\Sigma(\theta)$  is the model-implied covariance matrix (Bollen 1989). In contrast with conventional statistical models, where the rejection of a null hypothesis is sought, the goal of structural equation modeling is acceptance of the null hypothesis, and thus statistical validation of the proposed model. The model is fitted by minimizing the differences between observed and model-predicted covariances.

In this study, a hypothetical initial model was elicited for each waterbody, which then was evaluated for fit and parsimony. This model was then compared with all other models containing the same exogenous and endogenous variables (nested analysis)(Bollen 1989).

## **2.4 Case Studies**

### **2.4.1 Lake Washington**

Lake Washington is the second largest natural lake in the State of Washington, and is one of the best documented cases of successful restoration by sewage diversion (Edmonson 1994). The lake received increasing amounts of secondary treated sewage between 1941 and 1963, which resulted in severe eutrophication, cyanobacteria dominance, and declining water quality. Sewage was diverted between 1963 and 1967, with discharge of wastewater treatment plant effluent (except for combined sewer

overflows) eliminated by 1968. Rapid water quality improvements followed, cyanobacteria abundance declined dramatically, *Daphnia* population resurgence occurred in 1976, dominating the summer zooplankton community since. Currently, Lake Washington can be characterized as a mesotrophic ecosystem with limnological processes strongly dominated by a recurrent diatom bloom, which occurs during March and April with epilimnetic chlorophyll concentration peaks on average at 10 µg/L, which is 3.2 times higher than the summer concentrations when the system is phosphorus limited (Edmonson 1994, Arhonditsis et al. 2004). Washington serves as prime habitat for juvenile salmon and supports both recreational activities and local fisheries (Kerwin 2001). Washington State submitted a proposed policy for nutrient criteria in 2003, pending approval by the USEPA under Section 303(c) of the Clean Water Act. Lake Washington's designated uses protect, for example: salmon and trout, primary contact recreation, domestic, water supply, wildlife habitat, commerce and navigation, boating, and aesthetic values (Washington State Department of Ecology 2003).

Data on standard limnological parameters were obtained from the Major Lakes Monitoring Program in King County, Washington State for 1994 – 2000. Zooplankton abundance and species composition were also provided by the Department of Biology, University of Washington (Arhonditsis et al. 2004). Dr. Eugene Welch, a Professor Emeritus at the University of Washington, was chosen as the expert for this study. Presented with Lake Washington's designated use statement (Washington State Department of Ecology 2003), Dr. Welch identified boating as the most appropriate

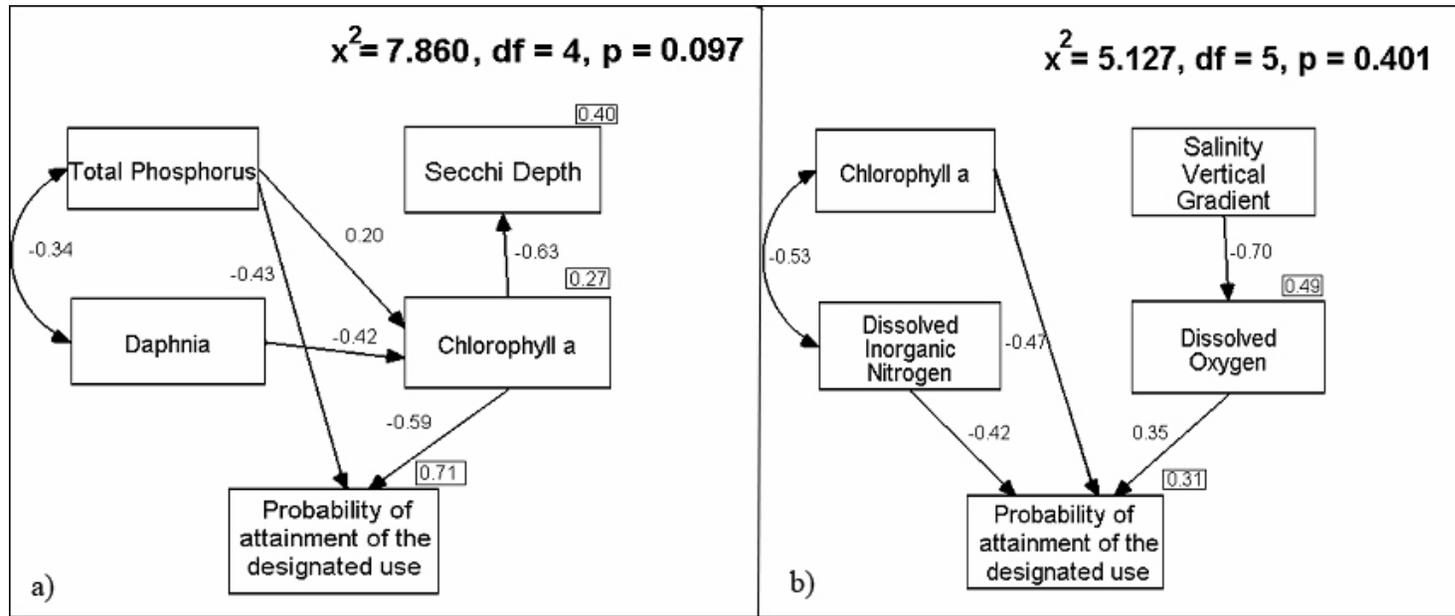
nutrient-related designated use to address based on his technical expertise. He selected water clarity, the absence of algal scums, odor, and interference from aquatic vegetation, as desired properties of a “boatable” lake. In addition, the expert provided a conceptual model that included chlorophyll *a*, total phosphorus, Secchi depth, total zooplankton, and *Daphnia* biomass as the key environmental variables for assessing attainment of the designated use. He hypothesized that chlorophyll *a* would be the water quality variable most closely linked to the desirable properties of a boatable lake.

The second phase of the elicitation related the expert-identified water quality variables to a quantitative estimate of the designated use attainment (i.e. boating). In accordance with the procedure discussed in the “Methods” section, a data matrix of fifty independent multi-variate observations was prepared and shown to the expert. The probability of use attainment was elicited for each data row and added as a new variable to the observation set.

A structural equation model was fit to the data matrix, using the elicited probability of use attainment as the response variable and the elicited conceptual model as the hypothetical initial model. The final model had relatively good fit, and all paths shown are individually significant ( $\alpha = 0.05$ ), except the path between total phosphorus and chlorophyll *a* (Figure 1a). The model explains 27% of the variation in chlorophyll *a* and 74% of the variation in the probability of designated use attainment. The standardized (i.e., the unstandardized partial regression coefficients multiplied by the ratio of the standard deviation of the explanatory variable to the standard deviation of

the variable it affects) direct effect of *Daphnia* grazing on phytoplankton was -0.425, while the positive (but non-significant) path between total phosphorus and chlorophyll *a* represents phenomenon which is quite common in the summer epilimnion (when most of the available phosphorus is sequestered in the phytoplankton cells). The standardized direct effects of chlorophyll *a* on the probability of designated use attainment were estimated to be -0.592, while no significant indirect pathway was included in the final model. On the other hand, the direct, indirect (via chlorophyll *a*), and total effects of total phosphorus on the probability of attainment of the designated use were -0.432,  $-0.116 = 0.195 \times (-0.592)$ , and  $-0.548 = (-0.432) + (-0.116)$ , respectively. Using the relative magnitudes of the various model paths to determine the ability of the water quality variables to predict use attainment, we can infer that chlorophyll *a* has a somewhat closer association (both direct and total effects) followed by the total phosphorus concentration. This result is consistent with the expert's judgement that chlorophyll *a* would be most closely linked to use attainment.

Thus, the basic contribution from our structural modeling approach can be described as: (i) development and testing of a model which in a straightforward way considers current conceptualizations of the system's dynamics, and (ii) use of the resultant ecological structure to assess the strength of the relationship between the predictor variables (the candidate water quality criteria) and the response variable (probability of attainment of the designated use).



**Figure 1: Structural Equation Models for Lake Washington and Neuse River Estuary**

Figure 1a is for Lake Washington and Figure 1b is for the Neuse River estuary. The numbers correspond to the standardized path coefficients and the R-squared values (numbers in rectangles);  $\chi^2$ ,  $df$  and  $p$  correspond to the chi-square test values, the degrees of freedom and the probability level for rejecting the null hypothesis, respectively.

## 2.4.2 Neuse River Estuary

The Neuse River Estuary, North Carolina, has a long history of excessive algal blooms, bottom water hypoxia, and fishkills. These problems led the Neuse River to be characterized as one of the 20 most threatened rivers in the United States in 1997 (American Rivers Foundation 1997). The Neuse has also been listed as an impaired waterbody on the Federal 303(d) list because, in certain segments, more than 10% of water quality samples analyzed for chlorophyll *a* exceeded the 40 µg/L criterion. Excessive chlorophyll *a* levels are generally attributed to high point source and non-point source inputs of nitrogen, though developing evidence suggests that phosphorus may sometimes contribute to excessive algal levels (Qian et al. 2000, Paerl et al. 2004). Therefore, in 1997, the North Carolina Division of Water Quality developed the Neuse Nutrient Sensitive Waters Management Strategy to reduce total nitrogen loading to the Neuse Estuary by 30% by the year 2003.

The designated uses of the Neuse River Estuary protect primary recreation, aquatic life propagation and maintenance of biological integrity, wildlife, secondary recreation, and any other usage except shellfishing for market purposes (North Carolina Department of Environment and Natural Resources 2003). Dr. Charles Peterson, Professor at the University of North Carolina, Chapel Hill (Institute of Marine Sciences) was the expert interviewed for this case study. Dr. Peterson indicated fish and wildlife protection as the designated use most closely related to his expertise. Maintenance of

fish populations of spot (*Leiostomus xanthurus*), croaker (*Micropogonias undulatus*) and benthic invertebrates were targeted as those most sensitive to eutrophication. The expert also provided a conceptual model of the basic Neuse River Estuary's eutrophication dynamics.

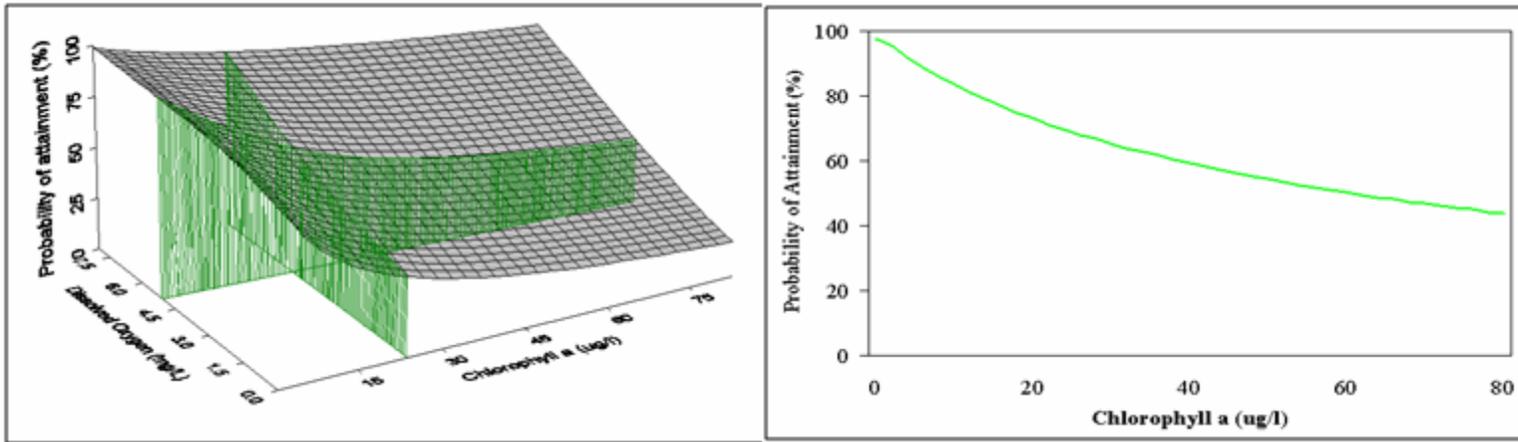
Dissolved oxygen had a central role in this model, as bottom water hypoxia often results from increased primary productivity in the euphotic zone that sinks and undergoes bacterial decomposition (Borsuk et al. 2001). Using the same framework as we used for Lake Washington (types of questions, recent data), we elicited experienced-based probabilistic judgments of the designated use attainment. The final Neuse River Estuary SEM is presented in Figure 1b, which can be interpreted in a similar way as it was indicated for Lake Washington.

We also applied this model to estimate the probability of use attainment associated with various levels of the candidate criteria; this provides a graphical expression of the risk of noncompliance. Figure 2a shows the predicted surface of the probabilities of use attainment based on the entire summer range of dissolved oxygen and chlorophyll *a* levels in the Neuse River Estuary, conditional on the concurrent dissolved inorganic nitrogen concentrations. In addition, this figure focuses on specific levels of each of the two candidate criteria (DO = 5 mg/L and chlorophyll *a* = 20 µg/L) and assesses the expected probabilities of use attainment conditional on the values of the other criterion (along with the DIN levels).

To provide an example of the potential use of the probability of attainment analysis, we created Figure 2b, which simplifies the analysis to two dimensions. Figure 2b graphically characterizes the relationship in the Neuse model between probability of attainment and the chlorophyll *a* concentration, conditional on a dissolved oxygen concentration of 5 mg/L. The probability expresses the uncertainty in the relationship between the attainment of designated use and the criterion level; it reflects uncertainty in the elicited expert judgment plus error and variability in the water quality data used to fit the model. Of particular importance to the decision on setting the water quality criterion level, the probability of attainment is a realistic quantitative assessment of our ability to assess compliance with the designated use based on a chlorophyll criterion level.

While recognizing that this is a test example (not intended as the final analysis leading to a recommended criterion and level), we should consider use of a graph like that in Figure 2b to examine the choice of chlorophyll *a* level based on willingness to accept risk of nonattainment. For example, the graph in Figure 2b indicates that the current chlorophyll *a* criterion in the Neuse of 40 µg/L yields only a 60% probability of attainment. Based on this analysis, to achieve a high likelihood of attainment, the chlorophyll *a* criterion would have to be less than 10 µg/L. Of course, absent from this assessment, but critical to standard setting, is the feasibility of achieving a particular

chlorophyll level. Nonetheless, Figure 2b still can inform the criterion decision by quantifying the risk of nonattainment.



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**Figure 2: Application of the Neuse River Estuary Structural Equation Modeling for Estimating the Probability of Attainment of the Designated Use**

We logit transformed the expert's response for the entire summer range of dissolved oxygen and chlorophyll *a* levels in the Neuse River estuary (Figure 2a). The two green surfaces correspond to specific levels of the two candidate criteria, i.e. dissolved oxygen = 5 mg/L and chlorophyll *a* = 20  $\mu$ g/L (the latter is also shown in Figure 2b).

## **2.5 Discussion**

In this paper, we approach water quality criteria setting from the prescriptive basis that criteria should be predictive of designated use and from the pragmatic basis that risk of nonattainment should be acknowledged and therefore considered when setting a level or concentration. Thus, from a prescriptive standpoint, a good criterion should be an easily measurable surrogate for the narrative designated use and should serve as an accurate predictor of attainment. Correspondingly, from a pragmatic perspective, natural variability and criterion-use prediction uncertainty will almost certainly result in some risk of nonattainment; thus the selection of a criterion level for the attainment-nonattainment transition realistically should be based on an acceptable probability of nonattainment. Furthermore, the selection of the acceptable probability is a value judgment best left to policy makers and should not be “hard-wired” into the criteria level analysis. Our approach has these attributes.

Once the procedure was developed, the major challenge in this work was the quantification of the narrative designated use statement. We opted for a two-stage expert elicitation with a single expert, as described previously. This procedure served largely as a proof-of-concept, essentially assuring us that we could successfully

undertake this analysis. While we are confident in this approach for nutrient criteria development, we intend to implement certain changes that we feel are necessary before the results should be used to establish criteria.

- The primary change is to consult multiple experts and to employ proper procedures to combine expert judgments (Kline 1998, Clemen and Winkler 1999); a single expert was convenient for this initial analysis, but criteria choice can be expected to be more robust when multiple experts are involved.
- An appealing alternative is to conduct a user survey that is undertaken concurrent with water quality modeling. The survey would ask users whether the designated use is currently being met; the concurrent water quality measurements would then serve as predictor variables in a structural equation model, while the user responses would serve as the response variable. (An example of a user survey protocol executed in North Carolina is included in Appendix B.)
- While we illustrated the procedure on single waterbodies in the paper, we envision that its actual usage would be on a cross-sectional data set (e.g., a random sample of lakes within an ecosystem, or state). Thus, in future applications, we will apply the approach to multi-waterbody cross sectional data. This should increase the variability in both the predictor and response variables spaces, which should improve model fit.

In directing the US USEPA to develop a national strategy for nutrient criteria, the President's 1998 Clean Water Action Plan lays the foundation for

addressing the leading cause of TMDLs nationwide. Given the estimated number of nutrient-related TMDLs required, and the costs/benefits of addressing these ambient water quality standard violations, it is clear that the choice of water quality criteria for eutrophication management and nutrient TMDLs has significant consequences. We believe that a better method to address this critical need is our predictive approach to nutrient criteria.

### **3. Selection of Nutrient Criteria Variables using the Predictive Approach for the Kissimmee Chain-of-Lakes in Florida using Structural Equation Modeling**

#### ***3.1 Introduction***

Florida recognizes eutrophication as one of the primary sources of waterbody impairment. Eutrophication is a condition fueled by excess nitrogen and phosphorus that causes problems such as anoxia and noxious algal blooms. To protect the nation's waterbodies from impairment, the Clean Water Act requires states to establish water quality standards. These water quality standards are designed to protect the designated use, or water quality goal; however, they are indirectly measured and assessed using the water quality criterion. Building on previous research by Reckhow et al. (2005) on the predictive approach to nutrient criteria and addressing the USEPA's national nutrient strategy, which requires states to protect designated uses by establishing nutrient criteria, we explored nutrient criteria setting for the Florida Kissimmee Chain-of-Lakes. In this study, we determined which measured water quality variables are most predictive of designated use attainment. These predictive variables were statistically determined, using structural equation modeling, by combining water quality data with data from multiple experts on the probability of designated use attainment. By examining the total effects of two competing models, we determined that total phosphorus was the most predictive of the designated use with chlorophyll a the second

most predictive variable. Using this information we were able to assess the risk of nonattainment of the designated use for these two predictive variables. This paper provides a particularly interesting extension to the previous approach through its use of multiple experts and a region of lakes, making the approach and conclusions suitable for policy implementation.

### **3.2 Background**

Florida currently identifies one of the primary sources of waterbody impairment to be excessive nutrients that cause eutrophication (Hand et al. 2000). Eutrophication is a process fueled by excess nitrogen and phosphorus that causes problems such as anoxia, noxious algal blooms, and fish kills (Novotny and Olem 1994, Chapra 1997). To protect the nation's waterbodies from excessive impairments, Sections 101(a) and 303(c) of the Clean Water Act require states to establish water quality standards.

Water quality standards contain an antidegradation clause, a qualitative designated use statement, and a qualitative or quantitative criterion. The antidegradation clause is a narrative statement that the water quality standards must prevent additional degradation of the waterbody use(s). The designated use is a narrative statement that articulates the water quality goal. The designated uses are set by States or Tribes and describe the desired uses of the waters; these designated uses can be classifications such as public drinking water supply, primary contact recreation, and support of aquatic life. Since the designated use cannot be directly measured, a criterion

serves as the scientific surrogate for the designated use; that is a measurement of the criterion is intended to indicate attainment (or nonattainment) of the designated use. The criterion is either a numeric measure or narrative statement which serves as an indicator of whether or not the designated use is met. Typically, the criterion is a combination of an easily measurable water quality variable and the criterion level for that variable; the critical level for the criterion provides a minimum threshold that must be maintained or attained to support the designated uses. Criteria have been set by States and Tribes for toxic chemicals (examples: metals or chlorine) and for water quality characteristics (examples: dissolved oxygen and temperature).

Currently, the USEPA is encouraging states to adopt nutrient criteria (Environmental Protection Agency 2000e). By nutrient criteria, USEPA means any measurable water quality variable or variables that can be used to detect eutrophication impairments (i.e. phosphorus, algae, water clarity, etc.) and the associated criteria levels. As a result, many states are currently evaluating the choice and level of criterion. This is not a trivial issue, and it has led to much debate about what method should be used to establish these standards.

The method to set nutrient criteria is left to the best judgment of the state; however, the most common method is the USEPA-endorsed Ecoregion Reference Waterbody strategy (Environmental Protection Agency 2000e, c). In its skeletal form, the Ecoregion Reference Waterbody approach has four steps. First, a State or Tribe chooses a water quality variable as the criterion. This variable can be any of the four

eutrophication-related variables, total nitrogen, total phosphorus, chlorophyll a, or Secchi depth. Second, a State or Tribe classifies waterbodies as either a reference waterbody or not a reference waterbody. Alternatively, a State or Tribe can take a representative sample of all the waterbodies in the ecoregion. Third, the State or Tribe plots a cumulative distribution of the variable chosen in step 1; they plot a distribution for the reference waterbodies and/or a representative sample of all the waterbodies. Last, the criterion level is set at either the 75<sup>th</sup> percentile of the distribution for the reference waterbodies or the 25<sup>th</sup> percentile of the distribution of the representative sample of all the waterbodies (Environmental Protection Agency 2000e, c).

Though this method is one possible approach at setting criteria, it has two major flaws. First, it fails to substantively link the criteria to the designated use, meaning that the criterion variable is not necessarily a good predictor of designated use attainment. Second, it fails to distinguish between the science and societal values, making the implicit risk-based decision incorporated to set the criterion levels seem scientifically driven rather than the combination of science and value judgments (Environmental Protection Agency 2000e, Reckhow et al. 2005).

An alternative approach is the predictive nutrient criteria method (Reckhow et al. 2005, Reckhow et al. 2006, Kenney 2007). This method uses a combination of water quality data, expert elicitation, and structural equation modeling to determine the variable that is most predictive of designated use attainment (Reckhow et al. 2005). This process explicitly considers the risk of nonattainment of the water quality goal and

presents a procedure to quantify the appropriateness of candidate nutrient criteria. As a result, this method provides an improvement over the Ecoregion Reference Waterbody by developing a method that explicitly addresses the two flaws.

Therefore, in this paper, we choose to use the predictive approach to nutrient criteria to explore nutrient criteria setting for the Florida Kissimmee Chain-of-Lakes. In this study, we determined which measured water quality variables are most predictive of designated use attainment. These predictive variables were statistically determined, using structural equation modeling, by combining water quality data with data from multiple experts on the probability of designated use attainment. This paper provides a particularly interesting extension to the approach used by Reckhow et al. (2005) through its use of multiple experts and a region of lakes, making the approach and conclusions suitable for policy implementation.

### **3.3 Methods**

#### **3.3.1 Study Site and Data**

The region of lakes used in this study was the Kissimmee Chain-of-Lakes located in south-central Florida (Figure 3). The six lakes in this region are: Lake Okeechobee, East Lake Tohopekaliga, Lake Tohopekaliga, Cypress Lake, Lake Hatchineha, and Lake Kissimmee (Figure 1). All of these lakes are located in a region with similar weather patterns, general lake dynamics, and similar seasonal physical, chemical, and biological trends and attributes (Havens 2005). These lakes are shallow (2-5 meters) and

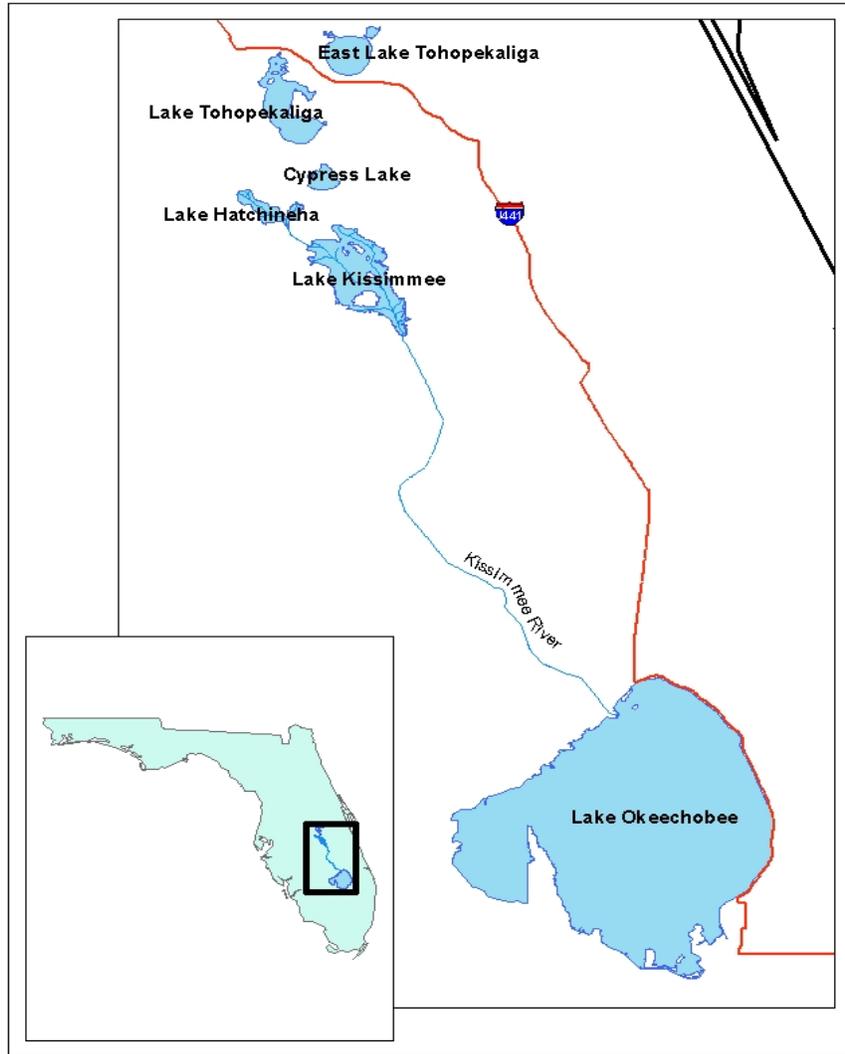
encompass a wide range of trophic states (Havens 2003). The summary statistics for the untransformed variables used in the analysis are provided in Table 1.

All six of the lakes are eutrophic, except for East Tohopekaliga, which is considered mesotrophic. East Tohopekaliga has some of the highest color values (>200 platinum-cobalt unit (PCU) during rain events), but it has low chlorophyll a, total nitrogen, and total phosphorus values. All of the lakes in this region are highly regulated and have been periodically drawn down for Hydrilla control and muck removal (Havens 2005).

This system of lakes has several designated uses, but for the purposes of this study, we chose the designated use that we felt was the most stringent. The designated use that we specifically considered was “the propagation and maintenance of a healthy, well-balanced population of fish and wildlife (Rule 62-302.400, Florida Administrative Code).” This designated use addresses the Florida Class III classification, with the exclusion of the Class III use of “Recreation.”

**Table 1: Summary statistics for the eutrophication-related water quality variables**

	Mean	Standard Deviation	Minimum	Maximum	Skewness	Kurtosis
Chlorophyll a (µg/L)	18.68	18.12	1.00	97.41	1.65	3.50
Total Phosphorus (mg/L)	0.05	0.03	0.01	0.15	1.54	2.60
Total Nitrogen (mg/L)	1.03	0.33	0.25	2.32	0.69	1.34
Total Kjeldahl Nitrogen (mg/L)	1.02	0.34	0.25	2.31	0.65	1.44
15 Dissolved Inorganic Nitrogen (mg/L)	0.04	0.05	0.01	0.21	1.92	3.04
Total Suspended Solids (mg/L)	5.61	6.91	0.50	36.50	2.18	6.06
Color (PCU)	91.01	62.06	24.00	267.98	1.27	0.91
Secchi (m)	0.91	0.44	0.20	2.60	1.25	1.82



**Figure 3: Kissimmee Chain-of-Lakes in South-central Florida**

The lakes in this region from north to south include East Lake Tohopekaliga, Lake Tohopekaliga, Cypress Lake, Lake Hatchineha, Lake Kissimmee, and Lake Okeechobee.

### **3.2.2 Dataset**

The South Florida Water Management District (SFWMD) conducts routine monthly water quality sampling and collects data on standard limnological parameters. The dataset for the six lakes in the Kissimmee Chain-of-Lakes was obtained from the SFWMD's database (South Florida Water Management District 2007). This dataset which ranged from January 1995 to December 2001 consisted of the entire annual cycle of the following water quality variables: Chlorophyll  $\alpha$ , total nitrogen, total phosphorus, Secchi depth, color, total suspended solids, nitrogen oxide, ammonium, total Kjeldahl nitrogen, and organophosphate (Table 1).

The dataset was reduced by omitting observations with any missing values. Next, a subset of 100 data rows was constructed. This subset was determined to be an accurate representation of the full dataset by comparing the correlation coefficients of each variable in both the full and reduced dataset.

### **3.2.3 Expert Elicitation**

Since there is no way to directly measure designated use attainment, we conducted an expert elicitation to assess designated use attainment given typical water quality data. The expert elicitation protocol was similar to the approach used in Reckhow et al. (2005), which was based on expert elicitation best practices (Morgan and Henrion 1990, Keeney and Von Winterfeldt 1991, Meyer and Booker 1991, Clemen and

Reilly 2001). Similar to the Reckhow et. al. approach we designed our elicitation to have two parts: (1) an interview where the expert translates the narrative designated use, and (2) a probability exercise to quantify the designated use for 100 correlated water quality data rows. The primary outcome, for the 100 rows of water quality data, was a probabilistic judgment of designated use attainment for each of the water quality data rows. We assisted the experts in making this judgment, by asking them to look at each individual data row, considering all the water quality variables and their levels in that data row, and answer the question: "Given 100 hypothetical lakes in the Kissimmee Chain-of-Lakes, all with identical average levels of these variables and assuming other factors (e.g., morphological, climatic) vary randomly, how many of the 100 lakes would be in attainment of the given designated use?" We used the image of 100 lakes to assist the experts in thinking about the question probabilistically; this means of assessment also provided a way of directly translating between the assessment and the probability (i.e. an assessment of 50 lakes = 0.5 probability of designated use attainment).

Learning from the previous expert elicitation (Reckhow et al. 2005), we made some changes to the protocol to improve this assessment. During the first part of the elicitation, we additionally asked the experts what they believed to be the ideal measurable variable to assess designated use attainment, the change (attainment/nonattainment) point of this variable, and the commonly measured water quality variables that could be used as proxies for the ideal variable. In the second part of the assessment, we asked the expert to explain their assessments and asked questions

about their judgments to check for consistency. Thus, we were able to check the experts' assessments so that we could assist the experts in providing judgments that are representative of their true beliefs as well as helping to reduce bias and increasing consistency. This change was particularly important given that experts are not always good at making probability assessments, particularly near the extremes (Meyer and Booker 1991, Clemen and Reilly 2001).

Since this expert elicitation included multiple experts, to use the expert judgment as a response variable, it is essential to combine the expert judgment into a combined designated use value. After careful consideration of multiple methods, such as Bayesian approaches and behavioral approaches, we decided to use equal-weighted averaging. We choose to use equal-weighted averaging because this method is extremely robust, performing in a manner similar to the other methods that we considered (Clemen and Winkler 1999). Furthermore, to employ some of the other expert combination techniques, it is essential to have additional information to appropriately weight the relative informativeness of one expert versus another expert (Clemen and Winkler 1999). Since we did not have information on each of the expert's ability to make probability assessments, particularly for designated use attainment, we were unable to make an informed decision about an appropriate expert weighting scheme, other than to weight the experts equally. (See Appendix A for additional details on the expert elicitation protocol.)

### 3.2.4 Structural Equation Modeling

We chose to use structural equation modeling in this project to better represent the known relationships that lead to eutrophication-related nonattainment of the designated use. This provided knowledge about which water quality variable would be the most informative to assess designated use attainment. The water quality data were from the dataset previously described and the designated use attainment data were from the expert elicitations.

Structural equation modeling (SEM) is a multivariate statistical technique that can be used to describe linear relationships among variables (Bollen 1989, Kline 1998, McCune and Grace 2002, Grace 2006). SEM is a more general extension of multiple regression where the causal relationship between the variables can be described with multiple linear equations that describe both direct and indirect effects (Bollen 1989). The SEM implies a covariance structure between the variables included in the model. Therefore, SEM is an excellent statistical technique to use when there are conditions, such as eutrophication, that can be described through causal interactions that can be represented by the covariance between variables (Arhonditsis et al. 2006, Grace 2006).

SEM is an a priori method. By this we mean that a researcher develops a model that is reflective of the background knowledge of how the system works and then the model is tested with data. Therefore, unlike with other approaches, when using SEM a researcher wishes to accept the null hypothesis ( $H_0$ : data matches model) because this means that the model is a plausible representation of the system (McCune and Grace

2002). Rejection of the null hypothesis indicates that the data do not support the model structure. Specifically, a SEM fit is tested by minimizing the difference, or residual, between the model-implied covariance matrix and the data-implied covariance structure (McCune and Grace 2002).

Since there is not one test statistic that can incorporate all of the different facets of model fit, we used multiple test statistics to determine the adequacy of the models.

There are a number of different test statistics that can be used to assess the overall fit of the model; we applied four widely-used methods to evaluate our models:  $\chi^2$ ,

Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), and Root Mean Square Error of Approximation (RMSEA) (Kline 1998). The  $\chi^2$  statistic indicates whether or not the

model, which is, in SEM, by definition overidentified, differs statistically from a just-identified version of the model; a nonsignificant model (accept the null hypothesis)

would not differ statistically as indicated by p-values  $> 0.05$ . The CFI is a test statistic that signifies the overall proportion of variance explained by the model; good fit is

indicated by a CFI  $> 0.9$ . The TLI adjusts for the proportion of explained variance, and a

model is considered to have good fit if the TLI  $> 0.9$ . Finally, the RMSEA is model fit

index that considers the model's residuals; an RMSEA  $< 0.1$  indicates a satisfactory

model representation.

In this study, we developed and tested multiple models that were a combined representation of the experts' knowledge of the conditions causing eutrophication in the Kissimmee Chain-of-Lakes and how those conditions affect designated use attainment.

By considering multiple models we were not limiting our conceptualization of the system, and we could determine if there are multiple models that may be plausible given the underlying causal structure.

## **3.4 Results**

### **3.4.1 Expert Elicitation**

We compared the results of the elicitation for the four experts. To assess how similarly the experts responded, we compared each row of data to the experts' responses. These comparisons were created by correlating each expert's responses against another expert's responses. If the experts responded exactly the same for all the data rows the correlation would be 1; a high correlation (greater than 0.5) is desirable to demonstrate that the experts are approaching the probability assessment similarly. Since each expert has different expertise and experiences, we would expect some variation, but not extreme differences between the experts.

The results of the correlation table indicate that the experts' responses were somewhat correlated (Table 2). Specifically, Expert 1 and Expert 3 were strongly correlated (0.74), while Expert 1 and Expert 4 (0.46) and Expert 3 and Expert 4 (0.57) were somewhat correlated. Finally, Expert 2 was negatively correlated with the other three experts, indicating that this expert's responses were fundamentally different from the other experts. This is largely because Expert 2 had a radically different definition of designated use attainment, in comparison to the other three experts. Expert 2 defined

the designated use solely as desirable sport fishing conditions, while the other three experts defined the designated use more broadly as healthy propagation and maintenance of native aquatic life at levels associated with unimpacted conditions.

Since we used multiple experts, it was important to combine the expert judgments for use in the structural equation models. The largest benefit of having multiple experts is collecting data from a diversity of sources of expertise; therefore, there should be a good reason to weight experts unequally or to exclude an expert from the dataset (Clemen and Winkler 1999). As a result, we created one dataset where we used all of the experts' assessments and used equal-weighted averaging, which is also referred to as the linear opinion pool method (Clemen and Winkler 1999). Since Expert 2's responses were quite different from the other three experts, we also developed a second dataset that excluded Expert 2's responses and equal-weighted averaged the other three experts' responses. By creating both of these datasets, we were able to assess the sensitivity of our model results to the expert-assessed designated use attainment variable.

### **3.4.2 Structural Equation Modeling**

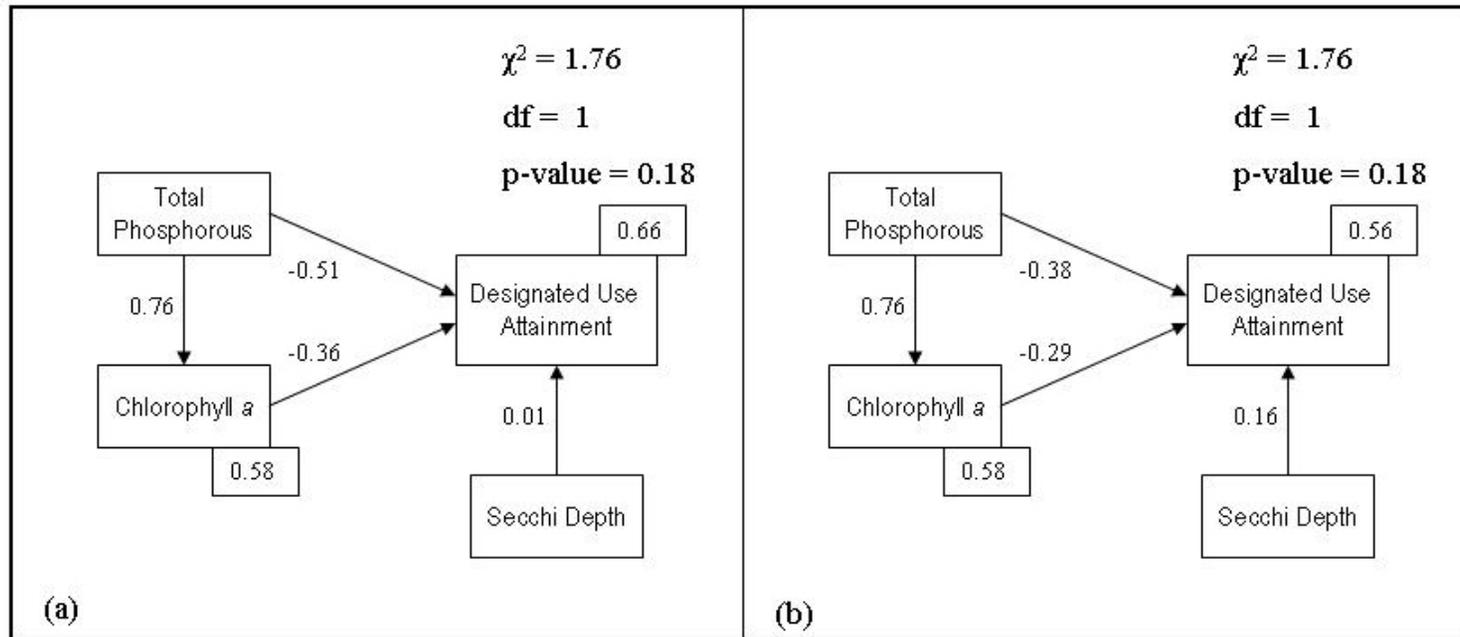
We developed and tested multiple structural equation models that represented our knowledge of eutrophication processes that lead to nonattainment of the designated use. Of these models, there were two models (Model 1 and Model 2) that demonstrated good fit.

**Table 2: Correlation of Expert Responses**

	Expert 1	Expert 2	Expert 3	Expert 4
Expert 1	1			
Expert 2	<b>-0.21</b>	1		
Expert 3	0.74	<b>-0.22</b>	1	
Expert 4	0.46	<b>-0.10</b>	0.57	1

Strong or moderate correlations indicate that experts 1, 3, and 4 were thinking similarly about designated use attainment, as indicated by similar responses to the probability assessment. Extremely low correlations are highlighted in bold; expert 2's responses were not correlated with any of the other experts.

Model 1 is a simple nutrient criteria model (Figure 4). In the model, increased total phosphorus levels directly affect chlorophyll a levels, describing the primary eutrophication process. Designated use attainment is directly affected by total phosphorus, chlorophyll a, and Secchi depth. In the model, increased levels of total phosphorus and chlorophyll a decreases the likelihood of designated use attainment; whereas, increased Secchi depth levels increase the likelihood of designated use attainment. All paths in this model, except for Secchi depth, are significant at  $p \leq 0.05$ . Model 1 was tested both with the dataset that included all experts (Figure 4b) and with the dataset that excluded Expert 2 (Figure 4a).



**Figure 4: Structural Equation Model 1 for the Kissimmee Chain-of-Lakes for (a) Dataset without Expert 2 and (b) Dataset with All Experts.**

The values on the arrows are the standardized path coefficients and the values in rectangles are the  $R^2$  values. The  $\chi^2$  (Chi-squared test statistic),  $df$  (degrees of freedom), and  $p$ -value refer to a model fit test statistic;  $p$ -values  $> 0.05$  indicate good model fit. In this model, the most predictive variables are total phosphorus and chlorophyll a.

For the model that used the dataset which excluded Expert 2 (Figure 4a), the Chi-squared test statistic ( $\chi^2 = 1.76$ ,  $df = 1$ ,  $p\text{-value} = 0.18$ ) indicates that the model is a plausible representation. The other tests of model fit, such as CFI (0.996), TLI (0.98), and RMSEA (0.087), additionally provide support that the model is reasonable.

The standardized path coefficients in this model provide us with information on the relative strength of the relationships, regardless of the variable's units and scale, across the variables. In this model (Figure 4a), comparing the total effects from the standardized path coefficients, the most predictive variable is total phosphorus (direct effect = -0.51; indirect effect =  $0.76 * -0.36 = -0.27$ ; total effect =  $-0.51 + -0.27 = -0.78$ ); the second most predictive variable is chlorophyll a (direct effect = -0.36; indirect effect = 0; total effect = -0.36). In comparison, the other paths provide much less explanation of designated use attainment.

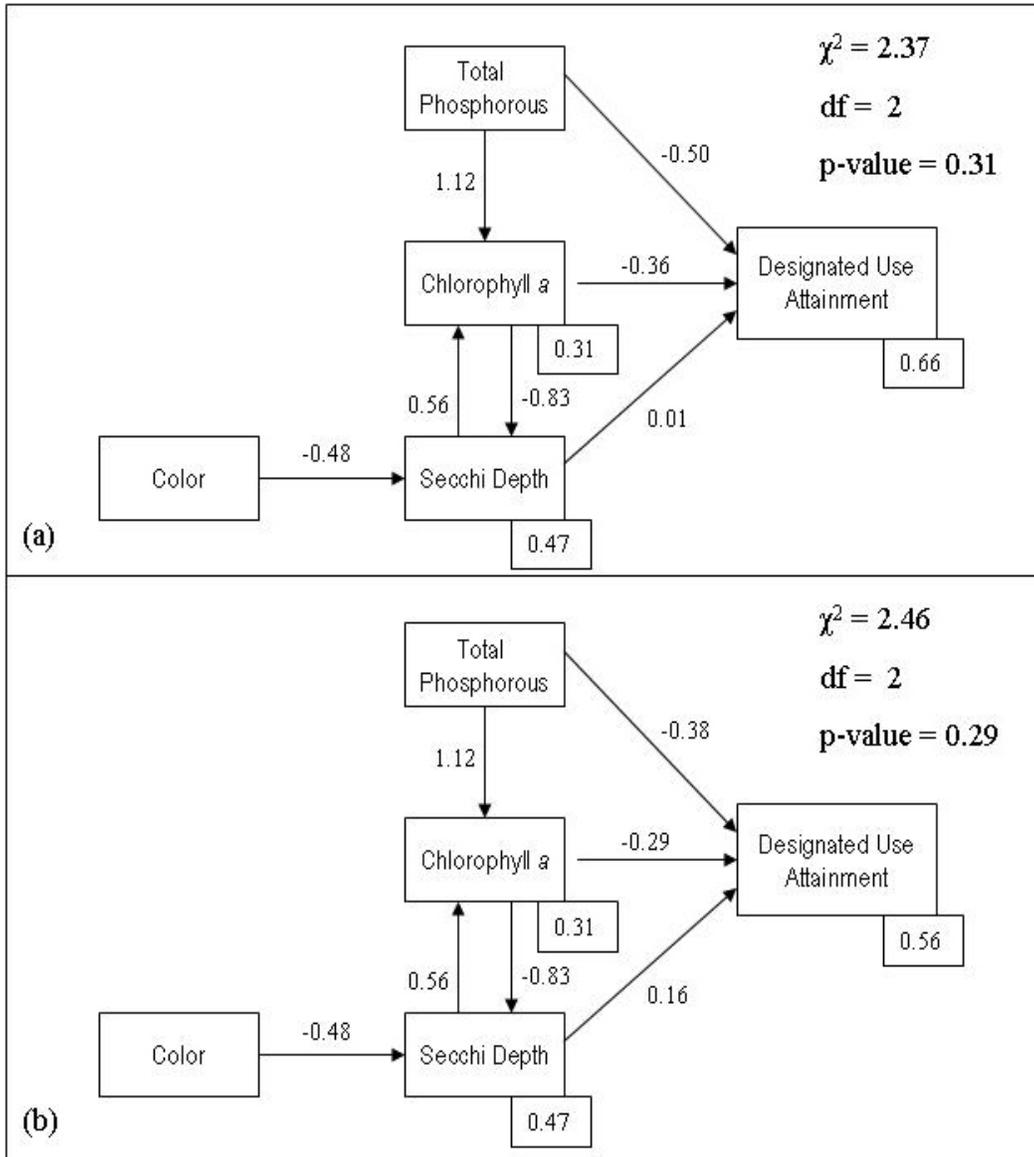
The  $R^2$  values for the model can be interpreted similarly to multiple regression. In this model a modest amount of variance is accounted for by chlorophyll a (0.58), whereas a considerable proportion of variability is explained for designated use attainment (0.66).

Model 2 is a slightly more complex nutrient criteria model (Figure 5a). In this model, increased levels of total phosphorus and Secchi depth cause increased levels of chlorophyll a. Increased chlorophyll a and color cause a decrease in Secchi depth. Increased levels of total phosphorus and chlorophyll a decreases the likelihood of designated use attainment; whereas, increased Secchi depth levels increases the

likelihood of designated use attainment. All paths in this model, except for the path between Secchi depth and designated use, are significant at the 5% level. Similar to Model 1, Model 2 was tested both with the dataset that included all experts (Figure 5b) and with the dataset that excluded Expert 2 (Figure 5a). Color was added to this model because allochthonous organic substances are the primary driver of color and affect the Secchi depth and trophic status (Canfield and Hodgson 1983).

For the model that used the dataset which excluded Expert 2 (Figure 5a), the Chi-squared test statistic ( $\chi^2 = 2.37$ ,  $df = 2$ ,  $p\text{-value} = 0.31$ ) indicates that the model is reasonable. The other tests of model fit, such as CFI (0.999), TLI (0.994), and RMSEA (0.043), additionally provide support that the model is a plausible representation. The interpretation of the predictive variables and  $R^2$  values is similar to Model 1a.

For comparison sake, we also tested the models (Models 1b and 2b) with a designated use attainment dataset that included all of the experts (Figures 4b and 5b). Using the model fit test statistics and the path coefficients, the results of the models with the dataset of all experts, 1b and 2b, were similar to their 1a and 2a counterparts. Of particular note, the most predictive variables and direction of the path coefficients remained the same. The main difference is the value for the standardized path coefficients; since Expert 2's responses were very different from the other experts, it is likely that the loss in the relative strength in the total phosphorus and chlorophyll a path coefficients is a result of the inclusion of Expert 2's responses.



**Figure 5: Structural Equation Model 2 for the Kissimmee Chain-of-Lakes for (a) Dataset without Expert 2 and (b) Dataset with All Experts**

The values on the arrows are the standardized path coefficients and the values in rectangles are the R<sup>2</sup> values. The  $\chi^2$  (Chi-squared test statistic),  $df$  (degrees of freedom), and  $p$ -value refer to a model fit test statistic;  $p$ -values > 0.05 indicate good model fit. In this model, the most predictive variables are total phosphorus and chlorophyll a.

Since there are two plausible models (using dataset excluding Expert 2), it is reasonable to compare the relative fit of the two models to see if one of the models outperforms the other model. To compare the two models, we used the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC); smaller values of both of these information criteria indicate better model fit. Comparing the models, Model 2a (AIC = 606.4, BIC = 632.5; sample-size adjusted BIC = 600.9) outperforms Model 1a (AIC = 610.5, BIC = 626.2; sample-size adjusted BIC = 607.2). Even though Model 1a has a lower BIC than Model 2a, Model 2a has a lower sample-size adjusted BIC as well as a lower AIC, indicating that Model 2 has better model fit. Overall, the differences between the models are very slight, and both models indicated that total phosphorus and chlorophyll a, in that order, are the most predictive variables.

We applied the model to consider the probability of designated use attainment for various levels of the two most predictive variables, total phosphorus and chlorophyll a. Using these variables, we considered appropriate candidate criterion levels by plotting the variables against a logit transformation of the average experts' responses. The values of the other variables were set to their mean values; this assumption means that the uncertainty is understated since we did not consider the full range of the other variables. We considered the two candidate criteria (Figure 6) and a single total phosphorus or chlorophyll a criterion (Figure 7a,b).

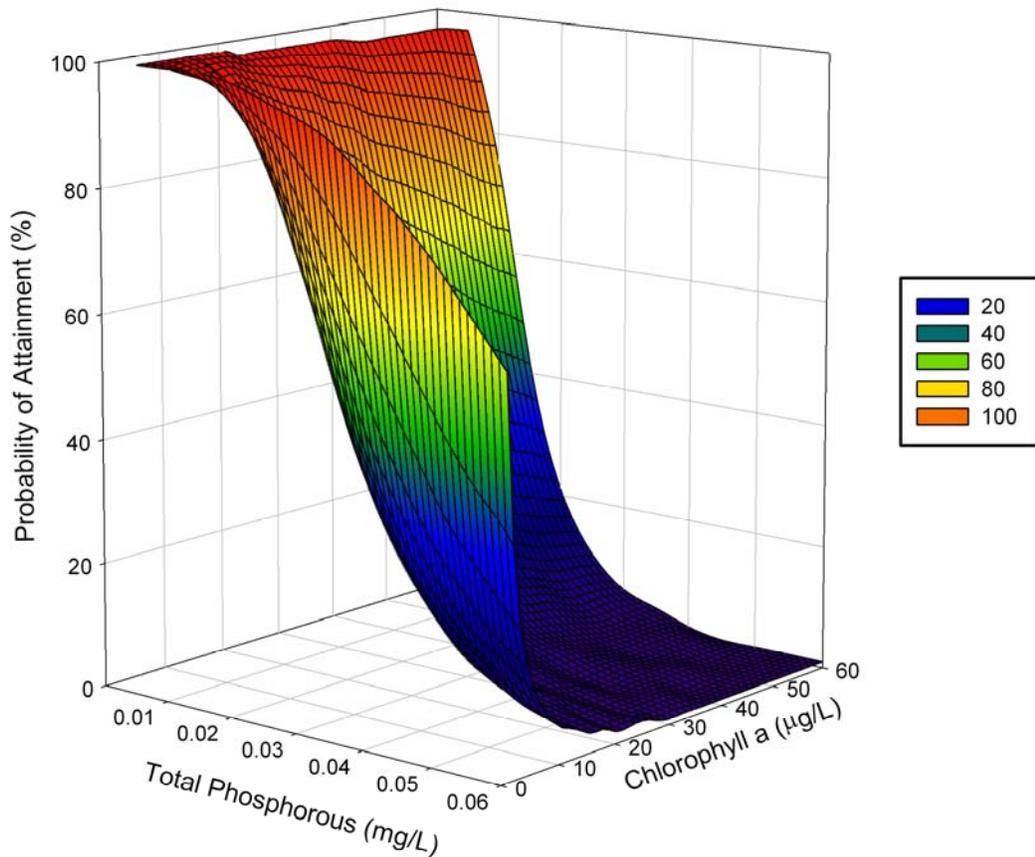
Figure 6 presents the surface of the probability of designated use attainment for total phosphorus and chlorophyll a (over a range of most-likely values of both

variables), conditional on Secchi depth remaining constant. Using this graph, a decision-maker could determine their risk of noncompliance of the designated use and assess which levels of total phosphorus and chlorophyll a would lead to an acceptable level of attainment.

Instead of considering a surface of potential values, we can consider the same problem in two-dimensions for total phosphorus (Figure 7a) and chlorophyll a (Figure 7b). For total phosphorus (Figure 7a), the probability of designated use attainment remains high when the total phosphorus levels are less than 0.015 mg/L and then dramatically decreases until it levels out at 10% or less attainment of designated use when total phosphorus values are greater than 0.05 mg/L.

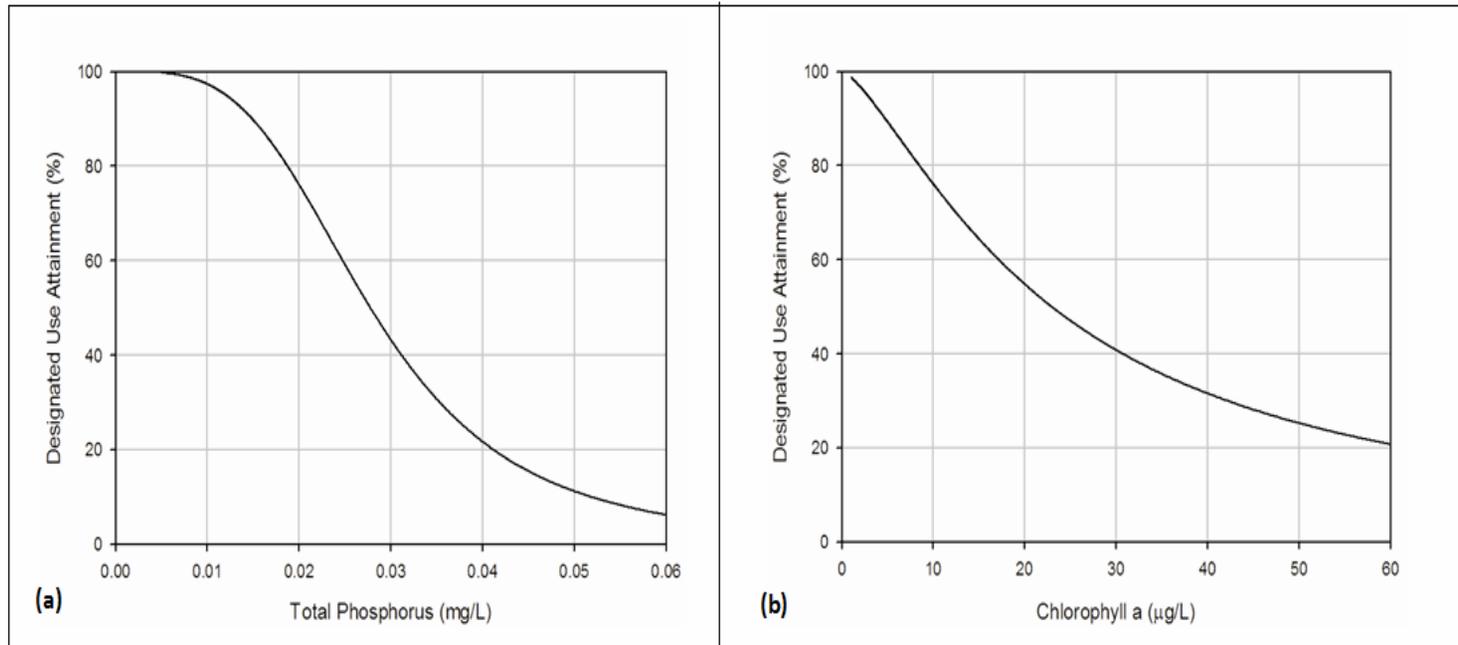
For chlorophyll a (Figure 7b), the figure exponentially decays over the range of values. Therefore, the chlorophyll a values must be less than 5  $\mu\text{g/L}$  to achieve a high (90% or greater) attainment of the designated use; setting a chlorophyll a criterion level at a value such as 30  $\mu\text{g/L}$  would yield a 40% attainment of the designated use. Taking into consideration the curvature of the two-dimensional graphs of both the total phosphorus (Figure 7a) and chlorophyll a (Figure 7b) explains the shape of the three-dimensional surface of probability of designated use (Figure 6) when the values are combined.

## Probability of Designated Use Attainment for the Kissimmee Chain-of-Lakes



**Figure 6: Three-dimensional Surface of Probability of Designated Use Attainment for Nutrient Criteria, Total Phosphorus and Chlorophyll a**

The average expert response is logit transformed, and the criteria levels are for the most likely range of summer values for both of these variables. The values in red/orange indicate a high probability of designated use attainment; values in blue indicate a low probability of attainment of the designated us



**Figure 7: Two-dimensional Graph of a Probability of Designated Use Attainment versus the Candidate Criterion for (a) Total Phosphorus and (b) Chlorophyll a**

### **3.5 Discussion**

Given the variety of expert judgments, we were able to capture this range of judgment by using multiple experts and then aggregating their designated use attainment judgments for application in the models for the Kissimmee Chain-of-Lakes. The inherent variability in the experts' responses, particularly when you seek and assess such a diverse group of experts as we did in this study, stresses the need to use multiple experts when making such assessments. By using multiple experts and combining their judgments, we are able to summarize a group of experts' accumulated probabilistic knowledge on the topic (Clemen and Winkler 1999).

The structural equation modeling results highlight that there is uncertainty in constructing the best model structure to link eutrophication and designated use attainment. Since we were able to develop two plausible models that fit the data well, we presented both of these models in our results. We are confident that our results are appropriately identifying the most predictive variables since both of the models indicated that the same variables were predictive of the designated use, total phosphorus and chlorophyll a.

Additionally, using the model results, we were able to present an analysis of the risk of nonattainment of the designated use. A decision-maker can use such information to set a criterion level or criteria levels based on their risk of nonattainment of the

designated use. Using our graphs to consider the probability of designated use attainment for the Florida Ecoregion XII Reference Waterbody (Environmental Protection Agency 2000c) nutrient criteria values, our graphs indicate that the recommended criterion of total phosphorus at 0.01 mg/L would lead to a 97% attainment of the designated use and the recommended criterion of chlorophyll a at 2.6 µg/L would lead to a 95% attainment of the designated use. A key difference between our method and the USEPA Ecoregion Reference Waterbody approach is that with our approach a decision-maker would determine what they believed was an acceptable probability of designated use attainment and then use the graph to set the criterion level. This is an important distinction because a decision-maker may determine that a 90% probability of designated use attainment would be acceptable to her, which would mean to that a better criterion level would be a total phosphorus or chlorophyll a level higher than suggested by the USEPA approach. Therefore, the USEPA approach for setting criteria for Florida lakes may be overly conservative for some decision-makers and perhaps not feasible or obtainable given the water quality levels reported in Table 1. The assessment does not, however, assess the feasibility of attaining the set water quality variable level.

One of the current weaknesses of using our approach is that the approach does not recommend a specific nutrient criterion level (Kenney 2007). We do not recommend a specific criterion level because doing so requires a decision maker's value trade-off

between environmental protection and waterbody research and implementation costs, or a decision maker's utility function. Therefore, our suggesting a criterion level would cloud the difference between scientific assessment and value judgments; ideally, this difference should be transparent. Therefore, for this research to have practical application, it would be useful to develop a procedure to assist policy makers in setting a nutrient standard based on their utility functions (Kenney 2007).

Future research directions should additionally include an extension of this approach to a state-wide assessment, with multiple ecoregions and multiple designated uses, for nutrient criteria development. Given the importance of setting appropriate water quality standards to determine whether a waterbody should be classified as impaired or not, it is essential for decision-makers to make the best assessment given the available data. Using our approach, we are able to provide this information, while linking the water quality variable to the designated use and transparently separating between science and value judgments, to help states make a decision to address setting nutrient criteria.

## **4. Use of Predictive Models to Select Nutrient Criteria Variables for North Carolina Lakes and Reservoirs**

### ***4.1 Introduction***

One of the major sources of lake and reservoir impairment is eutrophication. To protect against these impairments, the USEPA is encouraging States and Tribes to set nutrient criteria. One of the two important decisions in selecting nutrient criteria is determining which water quality variable(s) can best predict eutrophication-related impairments of the designated uses. To address this issue we used water quality data, expert elicitation, and three statistical models (structural equation models, multiple regression, binomial multiple regression). Using and applying the models to North Carolina, we determined that chlorophyll a, total phosphorus, and Secchi depth / turbidity, in that order, were the most predictive of designated use status. Also, given the expert elicitation judgments and models for North Carolina, there was no justification for selecting ecoregional criteria variables since the statewide criteria performed equally well. Finally, the models indicated that the variables that were most predictive of eutrophication were also the most predictive of the designated use. This finding is perhaps the most important since it has wide-reaching implications for evaluating predictive nutrient criteria variables in other regions. The approaches

presented in this article provide a substantive basis for the selection of water quality variables to use as proxies for designated uses.

## **4.2 Background**

The US Environmental Protection Agency (USEPA) proclaimed nutrients to be the number one cause of water quality pollution for lakes, reservoirs, and ponds, causing the eutrophication of 3.8 million acres of waters (Environmental Protection Agency 2002). Eutrophication is a condition fueled by excess nutrients, such as nitrogen and phosphorus, which can lead to undesirable outcomes such as anoxia, noxious algal blooms, and fish kills (Novotny and Olem 1994, Chapra 1997). To protect the nation's waterbodies from excessive impairments, Sections 101(a) and 303(c) of the Clean Water Act require states to establish water quality standards.

Water quality standards are set using an antidegradation clause, a qualitative designated use, and a qualitative or quantitative criterion. The antidegradation clause is a narrative statement that the designated use cannot be demoted because of degraded water quality conditions. The designated use is a narrative statement that describes the water quality goal, such as fishable and swimmable. The criterion is a numeric measure, such as dissolved oxygen  $\geq 5$  mg/L, or narrative statement, such as "free from substances that produce undesirable or nuisance aquatic life," that serves as a scientific surrogate

for the designated use; the criterion is a combination of a water quality variable and the criterion level for that variable.

Because eutrophication is a condition of a waterbody, several measured water quality variables are candidate water quality criteria. Using water quality criteria as surrogates for eutrophication-related designated use attainment can lead to increased risk and uncertainty in TMDL assessments (Borsuk et al. 2002b), which in turn can lead to misdiagnosis of waterbodies as out of compliance and expenditures on unnecessary mitigation measures. The reverse is also true and equally problematic; waterbodies that should be listed as impaired could be improperly diagnosed, resulting in waterbodies that fail to attain their uses, but are not subject to mitigation.

To address the important issue of properly evaluating whether or not a waterbody is impaired from eutrophication, the USEPA encourages States and Tribes to set numeric nutrient criteria (Environmental Protection Agency 2007), by which is meant any measured water quality variable and criterion level that can be used to detect eutrophication and measure the extent of the impairment. Many States are struggling with this important, complex decision, which requires making trade-offs between maximizing water quality and minimizing TMDL research and pollution mitigation costs.

In the past, the typical method used to set nutrient standards has been to consult government, consultants, and university scientists knowledgeable about eutrophication

conditions in the region and waterbody type of interest. This procedure is exemplified by the original process that North Carolina used to set nutrient standards in 1979 (Gray 2001). Recognizing the importance of maintaining their waters for secondary contact recreation, fishing, and aquatic life support (North Carolina Administrative Code 2003), the NC Division of Environmental Management examined the scientific literature on eutrophication and recommended, to an appointed panel of scientists, a chlorophyll a criterion level of 50 µg/L. The scientists reviewed research on the trophic status of North Carolina lakes (Weiss and Kuenzler 2001) and recommended revising the criterion level to 40 µg/L, because they felt that 40 µg/L more accurately reflected the transition point between impaired and unimpaired waterbodies.

In an effort to formalize the process to set nutrient criteria and in response to 303 of the Clean Water Act, USEPA developed guidance to assist States and Tribes in setting numeric nutrient criteria. As a result, the USEPA's Nutrient Strategy produced guidance, called the Ecoregion Reference Waterbody approach, which makes recommendations using a combination of science and expert judgments (Environmental Protection Agency 2000e). The choice of the criterion variable is based on the expert judgment regarding best measured proxy variable or variables and the criterion level or levels is/are chosen using a particular percentile from a cumulative frequency distribution of unimpacted waters, or reference waterbodies. The choice of how to

classify a reference waterbody versus a nonreference waterbody is a similarly subjective judgment.

Building on both of these methods, Reckhow et al. (2005) proposed a Predictive Approach to Nutrient Criteria, which was extended by Kenney et al. (in review). Their method recognized that criterion setting is a combination of science and expert judgments, but their approach was designed to incorporate quantitative expert judgments in a statistical model in order to identify criterion variables that are most predictive of designated uses. The big results of these studies were graphs showing the risk of nonattainment of designated use for various variables and threshold levels.

The goal of all of these methods is to identify those water quality variable(s) that can best determine eutrophication-related impairments. For other water quality standards there have been obvious proxy variables; however, no obvious surrogate for eutrophication exists because it is indicated by a combination of variables. However, we can use statistical models to identify the most predictive variables. In this study, to build on previous research published on nutrient criteria development, we examine two types of statistical models: (1) where the designated use is explicitly linked to the candidate nutrient criteria variables (as in Reckhow et al. 2005 and Kenney et al. in review), and (2) where we evaluate variables that are predictive of both eutrophication and designated use, testing the hypothesis that the variable that is most predictive of eutrophication is also the most predictive of the designated uses. We will present three

statistical modeling approaches, structural equation modeling, multiple regression, and binomial multiple regression. We apply these methods to North Carolina lakes and reservoirs to determine which water quality variable(s) are the best indicators of eutrophication-related designated use impairments.

### ***4.3 Site Description and Dataset***

We considered the nonflowing waters in the State of North Carolina. We evaluated water quality data for 132 North Carolina lakes and reservoirs (Figure 8) that are monitored by the North Carolina Department of Natural Resources, Division of Water Quality (NCDWQ). Most of these waterbodies are classified with multiple uses; however, we considered only two of these uses, primary contact recreation and secondary contact recreation. Primary contact recreation is defined as activities where there is likely full-body immersion of a human in the water, such as swimming or water skiing. Secondary contact recreation is defined as activities where a human could have dermal contact with the water, such as boating or fishing.

The data were obtained from the NCDWQ and included chemical, physical, and biological variables from 1981 - 2004. (See Appendix E for descriptive statistics for each of the North Carolina lakes and reservoirs.) We chose not to include data from 1997 – 2000 because incorrect laboratory procedures during this time resulted in unreliable data. We considered only seven eutrophication-related variables that are routinely

monitored: total nitrogen, total inorganic nitrogen, total phosphorus, chlorophyll a, dissolved oxygen, Secchi depth, and turbidity.

We binned the lakes and reservoirs into regions based on the USEPA Ecoregion Level IV boundaries (Omernik and Bailey 1997, Griffith et al. 2002) (Figure 8). North Carolina has four Ecoregions: Blue Ridge, Piedmont, Southeastern Plains, and Coastal Plains. For each ecoregion, we used a subset of the data to create a 100 x 7 matrix. Each of the 100 rows consisted of values for the seven water quality variables, which was representative of a waterbody from that region. Of these 100 data rows, 50 data rows were exactly the same for all ecoregions.

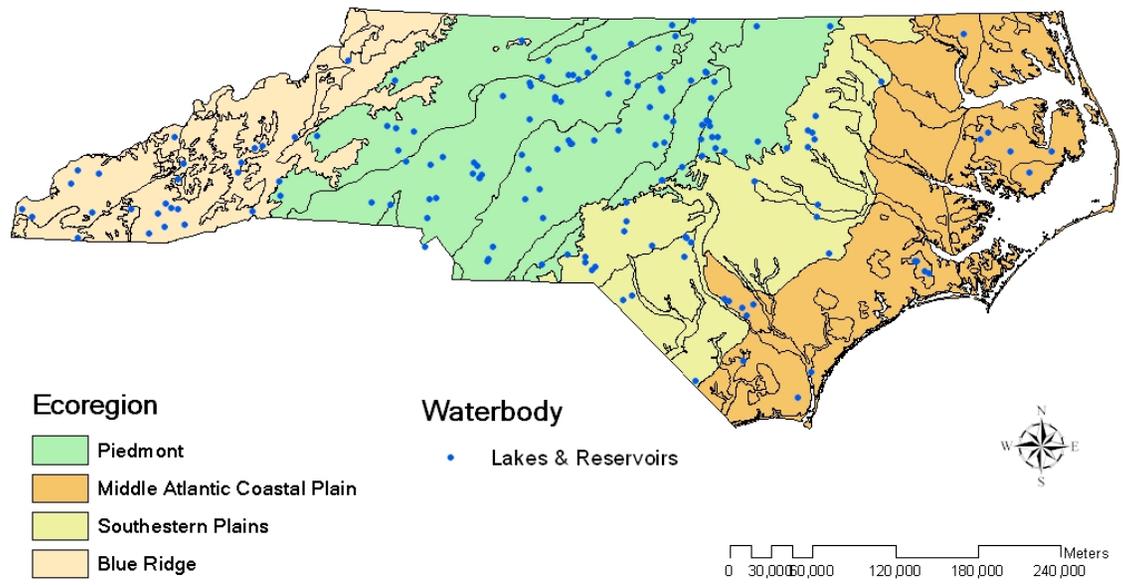


Figure 8: North Carolina Ecoregions and Lakes and Reservoirs

## **4.4 Expert Elicitation**

Our goal is to develop statistical models that link the seven water quality variables with a measure of a waterbody's eutrophication and designated use attainment, which were obtained in the form of expert probability judgments. Frequently used in the decision sciences, expert judgment has also been used in the environmental and aquatic sciences, although to a lesser extent (Reckhow 1988a, Anderson 2001, Borsuk et al. 2002b, Borsuk 2004).

Protocols for eliciting expert probabilities are described in Morgan and Henrion 1990, Keeney and Von Winterfeldt 1991, and Meyer and Booker 1991. The use of a carefully designed protocol can reduce judgment bias and improve the defensibility of the procedure.

Previous studies gathered expert judgments in two phases (Reckhow et al. 2005, Kenney et al. in review). The first phase consisted of the expert translating the designated use and providing a conceptual model of the major eutrophication processes for the study region. In the second phase of the elicitation, the expert assessed his or her subjective probability of designated use attainment, conditioned on the values of the water quality variables in each data row. Thus, each expert provided 50 or 100 conditional probabilities, one for each data row.

Although experts in the previous studies were able to provide the required conditional probabilities, this approach forced the expert to make the leap from the

water quality variables to designated use attainment, skipping the step of quantifying the trophic or eutrophication status.

In the elicitation protocol for the present study, experts were asked explicitly for their conditional probabilities of eutrophication status as well as designated use status, both of which were necessary for modeling nutrient criteria. The protocol to elicit these conditional probabilities contained four steps: (1) selection and preparation of the experts; (2) discussion with each expert individually of eutrophication conditions and designated use; (3) assessment of the conditional probabilities of the eutrophication categories and designated use categories for a region of waterbodies; and (4) a post-interview follow-up to calibrate the assessment and to confirm or correct the expert's judgment. The third and fourth steps were the most important; they quantified, on a categorical scale, both the eutrophication classification and the category level of designated use attainment. Then, the expert elicitation data were combined with the water quality data for use in the nutrient criteria models. In total, the entire elicitation took approximately six to eight hours of the expert's time.

#### **4.4.1 Expert Elicitation Protocol**

##### ***4.4.1.1 Step 1: Selection and Preparation of Expert***

In preparation for the expert elicitation, experts were identified, contacted, and informed of the elicitation tasks. Experts were identified by completing a thorough

search of academics, state scientists, and consultants that have knowledge of eutrophication for nonflowing waters in North Carolina or the Middle Atlantic region. All of the researchers who met the qualifications were contacted and asked to voluntarily participate in the study; we contacted all these individuals so that we could capture the range of expertise on eutrophication and designated use attainment through the use of multiple experts in each ecoregion. Those individuals who agreed to participate, or experts, were additionally informed of the elicitation tasks and the purposes of this exercise.

#### ***4.4.1.2 Step 2: Discussion of Eutrophication and Designated Use***

The second part of the elicitation was a face-to-face meeting with the expert. During this part we lead a directed discussion about eutrophication conditions and designated use impairment as well as the use of expert judgments in this project. This process took the between 1 – 2.5 hours.

We began the conversation by describing the project, why their assessments were necessary, the protocol for the elicitation, and how their judgments would be used in the analysis. Then, we moved to an open-ended discussion that was guided by two primary questions:

1. What are the mechanisms leading to eutrophication?

2. What other variables (not directly eutrophication-related) affect a waterbody's attainment of designated use?

These were not the only questions, because depending on how an expert responded, we would ask clarifying questions or probe into areas of the expert's specialty.

This part of the elicitation provided us perspective on how the expert views eutrophication and designated use attainment, particularly the similarities and differences between ecoregions in North Carolina. We also learned, during this process, which measurable variables the expert thought were most important to assess eutrophication and designated use; a judgment they would formalize in Part 3.

#### ***4.4.1.3 Step 3: Quantification of Eutrophication and Designated Use***

Part 3 of the elicitation was the most important part; it is where we asked the experts to provide a quantitative assessment, as a probability distribution, for eutrophication and the two designated uses. This part took approximately 2.5 – 4 hours.

Since we were not able to directly measure eutrophication or designated use and since there was not a natural scale or appropriate proxy, we created a constructed scale prior to the elicitation. Constructed scales are a great method to elicit information using descriptions that are meaningful to the expert (Keeney 1992). It is a particularly good

method when natural scales, such as money, are not readily available to express the quantity of interest, such as eutrophication status (Clemen and Reilly 2001).

The eutrophication (Table 3) and designated uses (Table 2) scales were created based on literature, consultation with water quality experts, and confirmation by decision analysts. The categories were the same for all four ecoregions.

We provided the experts with a booklet, specific to their ecoregion of expertise, where we described the probability assessment process in detail. In summary, each expert was asked to assess 100 different water quality data rows for eutrophication (Table 3) and the designated uses (Table 4) using the questions below:

1. Imagine 100 different lakes in the given ecoregion with the characteristics specified by the given data row. Of the 100 lakes, how many of the lakes would you expect to fall into each of the following five categories of eutrophication?
2. Imagine 100 different lakes in the given ecoregion with the characteristics specified by the given data row. Of the 100 lakes, how many of the lakes would you expect to fall into each of the five categories for the following designated uses?

We asked the experts to provide their responses as a distribution instead of simply indicating the most likely category. Having a probability distribution for each of their responses allowed the expert to cluster their response when they were more certain

and disperse their response when they were less certain. As a result, we were able to better represent the uncertainty in the expert's judgments and to understand which cases were the most challenging.

**Table 3: Eutrophication Categories / Trophic Status Categories Used in the Expert Elicitation Assessment of Eutrophication**

<b>Category</b>	<b>Description</b>
1	The lakes have: excellent water clarity, no color, very little algae, very low nutrient levels, very high oxygen, no odor, and very healthy, abundant aquatic life.
2	The lakes have: good water clarity, little color, little algae, low nutrient levels, high oxygen, little odor, and healthy, abundant aquatic life.
3	The lakes have: fair water clarity, some color, moderate amounts of algae, moderate nutrient levels, moderate oxygen, little odor, and somewhat healthy, abundant aquatic life.
4	The lakes have: poor water clarity, noticeable color, high algae, high nutrient levels, low oxygen, noticeable odor, and unhealthy, scarce aquatic life.
5	The lakes have: poor water clarity, considerable color, very high algae (likely scums), very high nutrient levels, low to no oxygen, strong offensive odor, and unhealthy, scarce aquatic life or no aquatic life.

**Table 4: Categories Used in the Expert Elicitation Assessment of Primary Contact Recreation and Secondary Contact Recreation**

1	Excellent: Greatly exceeds expectations
2	Very good: Exceeds expectations
3	Acceptable: Meets expectations
4	Fair: Below expectations
5	Poor: Far below expectations

To assure that the expert was approaching the probability assessment exercise properly, we worked through the first few cases with the experts until they felt comfortable and we were confident that they could properly work through the remaining cases on their own. After we received the expert's judgments in the booklet, we summarized both Parts 2 and 3 in a brief report. This report was sent to the experts; they could modify or fine-tune their judgments as they saw fit.

#### ***4.4.1.4 Step 4: Calibration of the Expert's Probability Assessment***

Using the expert's judgments from Part 3, we chose probability assessments that looked interesting or odd. These data rows were used in the follow-up phone conversation so that we could calibrate the expert's assessment. This phone conversation lasted from 1 – 1.5 hours.

During the follow-up we asked the experts to jointly look at two to three data rows and to justify the assignment of the probability for the data row. If the experts saw an error in their assessment, they were encouraged to make a correction that more accurately reflected their belief of the number of lakes that would fall into the eutrophication or designated use category. During this time, we also gained additional perspective of which variables a particular expert thought were important or not and how they made assessments for particularly difficult data rows. Any updates to the

assessments were included in the database, and the revised dataset was used for statistical modeling.

#### **4.4.2 Expert Judgment Combination**

When multiple experts are used to determine probability assessments, it is important to employ an appropriate method to combine the expert judgment (Winkler 1986). This method is contingent, in part, on the task required of the experts. There are multiple methods of expert combination that can be used to mathematically aggregate assessments. For this analysis, we chose to average the experts' judgments. We used averaging because it is a simple, effective method of expert combination (Clemen and Winkler 1990, 1999).

#### **4.4.3 Expert Elicitation Results**

We compared the expert responses for the 50 data rows that were the same for all the experts, regardless of the ecoregion, by evaluating how much agreement a given expert has with the other experts in a given region or within the entire state. Thus, if a single expert is largely out of agreement with all of the other experts, we can reevaluate whether or not we would use that expert in the analysis. In addition, we can also determine if there are systematic differences between the judgments of experts in one region of the state versus another region of the state.

The correlation tables (Tables 5 – 7) demonstrate that the experts, in general, agree with the other experts both in their ecoregion as well as in the other ecoregions. For the eutrophication assessment (Table 5), almost all of the experts' judgments had correlations of 0.5 or above. For primary contact recreation (Table 6), the correlations between experts similarly demonstrated that the experts reasonably agreed (above 0.5). There was one exception; C1's correlations with the other experts are consistently near zero. Since C1's correlations are near zero, this indicates that C1's assessments were very different from the other experts, leading to the question as to whether this expert's assessments should be included in a final dataset.

Finally, similar trends were seen in secondary contact recreation (Table 7). Overall, the correlations indicated that most of the experts were in agreement, but there were two assessments that were questionable, C1 and P3. These assessments, which are bolded in the table, are either negatively correlated with the other experts or have a correlation around zero. Again, this calls into question whether these assessments should be included in the final dataset.

To gain further insight about how well the experts agreed with each other and to assess whether all of the assessments should be included or whether we should exclude certain experts from particular elicitation variables, we calculated the average correlation of the experts between ecoregions (Table 8). By this we mean that, for each ecoregion, we averaged the individual correlations from Tables 5 – 7. As a result, we

can compare the average correlation of the experts for a particular ecoregion with the average correlation of the experts in a different ecoregion. In general, we would like to see average correlation values greater than 0.5.

**Table 5: Correlation Table of All the Experts in All the Ecoregions for their Assessment of Eutrophication**

	C1E	C2E	C3E	C4E	S1E	P1E	P2E	P3E	P4E	P5E	P6E	B1E	B2E	B3E
C1E	1													
C2E	0.70	1												
C3E	0.55	0.73	1											
C4E	0.39	0.66	0.73	1										
S1E	0.49	0.65	0.73	0.7	1									
P1E	0.57	0.72	0.66	0.62	0.76	1								
P2E	0.54	0.79	0.82	0.772	0.86	0.79	1							
P3E	0.47	0.62	0.43	0.34	0.58	0.70	0.60	1						
P4E	0.57	0.74	0.85	0.73	0.69	0.74	0.78	0.47	1					
P5E	0.53	0.62	0.85	0.69	0.81	0.71	0.86	0.42	0.79	1				
P6E	0.48	0.74	0.77	0.70	0.74	0.81	0.75	0.61	0.72	0.75	1			
B1E	0.48	0.59	0.62	0.58	0.72	0.77	0.70	0.49	0.58	0.68	0.70	1		
B2E	0.60	0.78	0.69	0.64	0.73	0.83	0.78	0.69	0.71	0.70	0.81	0.74	1	
B3E	0.64	0.80	0.67	0.64	0.64	0.76	0.75	0.63	0.77	0.70	0.72	0.67	0.80	1

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The correlations within ecoregions are indicated by the shaded areas

**Table 6: Correlation Table of All the Experts in All the Ecoregions for their Assessment of Primary Contact Recreation**

	C1P	C2P	C3P	C4P	S1P	P1P	P2P	P3P	P4P	P5P	P6P	B1P	B2P	B3P
C1P	1													
C2P	<b>-0.18</b>	1												
C3P	<b>0.09</b>	0.46	1											
C4P	<b>0.14</b>	0.50	0.69	1										
S1P	<b>-0.08</b>	0.79	0.63	0.60	1									
P1P	<b>-0.08</b>	0.89	0.48	0.51	0.81	1								
P2P	<b>-0.11</b>	0.77	0.69	0.63	0.83	0.78	1							
P3P	<b>-0.03</b>	0.92	0.55	0.55	0.81	0.91	0.82	1						
P4P	<b>0.02</b>	0.77	0.71	0.66	0.78	0.77	0.85	0.81	1					
P5P	<b>-0.14</b>	0.74	0.69	0.57	0.76	0.81	0.73	0.77	0.72	1				
P6P	<b>0.14</b>	0.58	0.64	0.66	0.77	0.67	0.68	0.67	0.71	0.64	1			
B1P	<b>0.02</b>	0.39	0.68	0.56	0.66	0.49	0.69	0.45	0.65	0.57	0.68	1		
B2P	<b>0.06</b>	0.81	0.62	0.63	0.83	0.86	0.76	0.85	0.81	0.78	0.74	0.54	1	
B3P	<b>-0.14</b>	0.88	0.44	0.46	0.75	0.86	0.78	0.88	0.77	0.73	0.59	0.41	0.80	1

The correlations within ecoregions are indicated by the shaded areas. Correlations that are particularly unusual are highlighted in bold; expert C1's assessment was not correlated with the other experts' assessments.

**Table 7: Correlation Table of All the Experts in All the Ecoregions for their Assessment of Secondary Contact Recreation**

	C1S	C2S	C3S	C4S	S1S	P1S	P2S	P3S	P4S	P5S	P6S	B1S	B2S	B3S
C1S	1													
C2S	<b>-0.42</b>	1												
C3S	<b>-0.37</b>	0.40	1											
C4S	<b>-0.23</b>	0.35	0.59	1										
S1S	<b>-0.59</b>	0.72	0.58	0.42	1									
P1S	<b>-0.49</b>	0.77	0.56	0.43	0.78	1								
P2S	<b>-0.57</b>	0.66	0.60	0.42	0.76	0.78	1							
P3S	<b>0.00</b>	<b>0.36</b>	<b>0.02</b>	<b>0.12</b>	<b>0.11</b>	<b>0.47</b>	<b>0.22</b>	1						
P4S	<b>-0.43</b>	0.67	0.61	0.45	0.62	0.74	0.68	<b>0.31</b>	1					
P5S	<b>-0.42</b>	0.70	0.67	0.45	0.72	0.78	0.66	<b>0.26</b>	0.71	1				
P6S	<b>-0.55</b>	0.51	0.62	0.55	0.73	0.57	0.59	<b>-0.06</b>	0.43	0.56	1			
B1S	<b>-0.59</b>	0.29	0.69	0.39	0.61	0.48	0.51	<b>-0.20</b>	0.38	0.50	0.68	1		
B2S	<b>-0.58</b>	0.71	0.50	0.59	0.80	0.76	0.68	<b>0.24</b>	0.67	0.69	0.66	0.48	1	
B3S	<b>-0.51</b>	0.84	0.45	0.32	0.79	0.85	0.77	<b>0.38</b>	0.77	0.75	0.52	0.36	0.74	1

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The correlations within ecoregions are indicated by the shaded areas. Correlations that are particularly unusual are highlighted in bold; the assessments from expert C1 and expert P3 were notably different from the other experts.

**Table 8: Average Correlation Table Between All Ecoregions for Eutrophication, Primary Contact Recreation, and Secondary Contact Recreation**

All Experts									
<b>Eutrophication</b>	CP	SEP	P	BR	CP	SEP	P	BR	
Coastal Plains (CP)	.63								
Southeastern Plains (SEP)	.64	XX							
Piedmont (P)	.65	.74	.70						
Blue Ridge (BR)	.64	.69	.71	.74					

All Experts					All Experts Except C1			
<b>Primary Contact Recreation</b>	CP	SEP	P	BR	CP	SEP	P	BR
Coastal Plains (CP)	.28				.55			
Southeastern Plains (SEP)	.48	XX			.67	XX		
Piedmont (P)	.49	0.79	.76		0.67	0.79	.76	
Blue Ridge (BR)	.45	0.74	0.72	.58	.61	.74	.72	0.58

All Experts					All Experts Except C1 and P3			
<b>Secondary Contact Recreation</b>	CP	SEP	P	BR	CP	SEP	P	BR
Coastal Plains (CP)	.05				.45			
Southeastern Plains (SEP)	.28	XX			.57	XX		
Piedmont (P)	.28	.62	.51		.58	.72	.65	
Blue Ridge (BR)	.26	.73	.56	.53	.53	.73	.64	.53

There is no value reported for SEP since that ecoregion only included one expert.

For eutrophication (Table 8), we included all the experts in the assessment and the average correlation was fairly high. As a result, there was no reason to consider excluding any of the experts from the dataset. For primary contact recreation, we calculated the average correlation for all of the experts and the average correlation excluding C1's assessments, for reasons discussed earlier (Table 8). Comparing the results, it is apparent that the inclusion of C1's assessments for primary contact recreation negatively affects the results of the correlations. For example, the average correlation of the coastal plains experts changed from 0.28 to 0.55 when C1's data were excluded. Similarly, we calculated the average correlation for secondary contact recreation that included all of the experts and all of the experts except C1 and P3 (Table 8). Again, comparing the results, the average correlations increase when C1 and P3's assessments were removed.

For use in the statistical models, we decided to use all of the experts' assessments of eutrophication. We included all the experts' eutrophication assessments because the experts were largely in agreement, particularly when we calculated the average expert correlation for each ecoregion. We made different choices for the designated uses. For primary contact recreation, we included all of the experts except for C1. We did not include C1's recommendations because when his assessments were included it drastically affected the results. Similarly, for secondary contact recreation, we chose not to include C1's and P3's judgments. Therefore, unless there was overwhelming evidence

that warranted excluding an expert's assessments, we included all expert judgments in the dataset for modeling. (See Appendix C for full expert elicitation reports for each of the experts included in the study.)

## **4.5 Statistical Modeling**

In this study, we used statistical modeling to examine the question of whether response variables, such as chlorophyll a or Secchi depth, or perhaps other chemical/biological/physical variables, such as total phosphorus or turbidity, are better predictors of eutrophication-related impairments of the designated use. The models were parameterized using a combination of water quality data and expert elicitation data. We used three statistical modeling methods to assess which variables are most predictive: structural equation modeling, multiple regression, binomial multiple regression.

### **4.5.1 Structural Equation Modeling (SEM)**

We used structural equation modeling (SEM) in this study to better predict designated use attainment by modeling the eutrophication process and linking this process to designated use attainment. Recently, structural equation modeling has been increasingly used by environmental scientists to represent some of the complexity inherent in environmental systems through explicitly modeling these relationships using measured and latent variables. (Grace and Pugsek 1997, 1998, Pugsek and

Grace 1998, Smith et al. 1998, McCune and Grace 2002, Weiher et al. 2004, Arhonditsis et al. 2006). Using SEM in this manner offers notable benefits in comparison to what is learned by examining single variable values (Grace 2006).

SEM is a multivariate statistical technique that can be used to describe relationships between variables through two or more linear equations. SEM has several attractive features. First, SEM allows us to model and test both the direct and indirect effects between variables. This allows us to represent processes, such as eutrophication, that can be better described by modeling both direct and indirect effects. Second, using SEM, one can explicitly incorporate measurement error uncertainty into the models (Bollen 1989). As a result, water quality variables not measured with perfect certainty can be incorporated into the model with uncertainty, assuring that the model estimators are not biased. Finally, SEM can include variables that are measured on ordinal or dichotomous scales. Thus, categorical data, such as expert elicitation or survey data, can be included and properly calculated using SEM.

With SEM, the goal is acceptance of the null hypothesis ( $H_0$ : data matches model), thus statistically validating the proposed model. We can use several different test statistics to evaluate the overall fit of the model. These include:  $\chi^2$  (good model: p-value > 0.05), Comparative Fit Index (CFI) (good model: CFI > 0.9), Tucker-Lewis Index (TLI) (good model: TLI > 0.9), and Root Mean Square Error of Approximation (RMSEA) (good model: RMSEA < 0.1) (Bollen 1989, Kline 1998). If all the test statistics indicate a

good model then the SEM is deemed a plausible representation of the ecosystem's structure. If the initial model is not the best representation, then the model is modified to better represent the studied system.

We developed a SEM based on our understanding of the relationships between the water quality variables, eutrophication, and designated use. This conceptualization was based on literature and the eutrophication conditions and designated use relationships in North Carolina, as described by the experts. The model was then modified to improve fit and parsimony.

#### **4.5.2 Structural Equation Modeling (SEM) Results**

We created SEMs to link the water quality data to eutrophication and the designated uses. We created separate models for the two designated uses, primary contact recreation and secondary contact recreation. Additionally, the models were created for the different ecoregions and for the entire state. In all, we created over 350 models. These models were developed by using the measured water quality variables to predict the eutrophication category and then linking the eutrophication category to the designated use category (Tables 9 and 10).

Most of the models developed did not produce reasonable (nonsignificant) results, but there were several models that were plausible and worked in more than one ecoregion (Tables 9 and 10). For both the primary and the secondary contact recreation

models, there was no model that had good fit in all of the ecoregions and the entire state. Since there is not a single model that surpassed the others, we considered each of the candidate models to determine which water quality variables would be the best candidate nutrient criteria variables.

For primary contact recreation (Tables 9 and 11), no model outperformed all others. The models that performed best were the single criterion models, or the models that used one water quality variable to predict eutrophication and then designated use. Models with more complex structures, tended to be less successful (nonsignificant in fewer ecoregions and the entire state).

To compare these models we used the Akaike Information Criterion (AIC) and sample-size adjusted Bayesian Information Criterion (BIC) values; for both of these information criteria smaller values more desirable. Comparing the AIC and BIC values for the nonsignificant models within each of the ecoregions and the nonnatural lakes throughout the entire state, models AP and BP performed the best overall (Tables 9 and 11).

Of these two models, the total phosphorus model is the more credible candidate. On one hand, Secchi depth cannot distinguish between algal-induced and sediment-caused turbidity and water clarity problems. Because many of the reservoirs in North Carolina suffer from nonalgal turbidity problems, Secchi depth is not a clean proxy for eutrophication-impairments. On the other hand, many North Carolina lakes are largely

recognized as phosphorus-limited systems; thus total phosphorus makes sense as a predictive variable.

**Table 9: Structural Equation Models for Primary Contact Recreation**

<b>Primary Contact Recreation Models</b>	<b>Coastal Natural Lakes</b>	<b>Coastal Non-natural Lakes</b>	<b>Southeastern Plains</b>	<b>Piedmont</b>	<b>Blue Ridge</b>	<b>North Carolina</b>
<b>Model AP</b> Eutro = $\beta_1$ Secchi DU = $\gamma_1$ Eutro	$\beta_1' = -0.59$ $\gamma_1' = 0.95$	$\beta_1' = -0.67$ $\gamma_1' = 0.95$	$\beta_1' = -0.53$ $\gamma_1' = 0.85$	$\beta_1' = -0.74$ $\gamma_1' = 0.95$	$\beta_1' = -0.89$ $\gamma_1' = 0.81$	$\beta_1' = -0.63$ $\gamma_1' = 0.94$
<b>Model BP</b> Eutro = $\beta_1$ TP DU = $\gamma_1$ Eutro	$\beta_1' = 0.39$ $\gamma_1' = 0.95$	$\beta_1' = 0.72$ $\gamma_1' = 0.95$	$\beta_1' = -0.07$ $\gamma_1' = 0.85$	$\beta_1' = 0.67$ $\gamma_1' = 0.95$	$\beta_1' = 0.62$ $\gamma_1' = 0.94$	$\beta_1' = 0.60$ $\gamma_1' = 0.94$
<b>Model CP</b> Eutro = $\beta_1$ Chla DU = $\gamma_1$ Eutro	$\beta_1' = 0.65$ $\gamma_1' = 0.95$	$\beta_1' = 0.03$ $\gamma_1' = 0.95$	$\beta_1' = 0.46$ $\gamma_1' = 0.85$	$\beta_1' = 0.73$ $\gamma_1' = 0.95$	$\beta_1' = 0.66$ $\gamma_1' = 0.94$	$\beta_1' = 0.69$ $\gamma_1' = 0.94$
<b>Model DP</b> Eutro = $\beta_1$ TP + $\beta_2$ Chla DU = $\gamma$ Eutro	$\beta_1' = 0.39$ $\beta_2' = 0.65$ $\gamma_1' = 0.95$	$\beta_1' = 0.79$ $\beta_2' = 0.25$ $\gamma_1' = 0.95$	$\beta_1' = -0.44$ $\beta_2' = 0.69$ $\gamma_1' = 0.85$	$\beta_1' = 0.53$ $\beta_2' = 0.60$ $\gamma_1' = 0.95$	$\beta_1' = 0.55$ $\beta_2' = 0.59$ $\gamma_1' = 0.94$	$\beta_1' = 0.55$ $\beta_2' = 0.65$ $\gamma_1' = 0.94$
<b>Model EP</b> Chla = $\beta_1$ TP + $\beta_2$ TIN Eutro = $\gamma_1$ Chla + $\gamma_2$ TP + $\gamma_3$ TIN DU = $\gamma_4$ Eutro	$\beta_1' = 0.17$ $\beta_2' = -0.54$ $\gamma_1' = 0.73$ $\gamma_2' = 0.33$ $\gamma_3' = 0.17$ $\gamma_4' = 0.95$	$\beta_1' = -0.15$ $\beta_2' = -0.39$ $\gamma_1' = 0.23$ $\gamma_2' = 0.80$ $\gamma_3' = -0.05$ $\gamma_4' = 0.95$	$\beta_1' = 0.46$ $\beta_2' = 0.08$ $\gamma_1' = 0.71$ $\gamma_2' = 0.12$ $\gamma_3' = -0.62$ $\gamma_4' = 0.85$	$\beta_1' = 0.26$ $\beta_2' = -0.03$ $\gamma_1' = 0.61$ $\gamma_2' = 0.48$ $\gamma_3' = 0.10$ $\gamma_4' = 0.95$	$\beta_1' = 0.25$ $\beta_2' = -0.36$ $\gamma_1' = 0.61$ $\gamma_2' = 0.05$ $\gamma_3' = 0.53$ $\gamma_4' = 0.94$	$\beta_1' = 0.17$ $\beta_2' = -0.25$ $\gamma_1' = 0.66$ $\gamma_2' = 0.53$ $\gamma_3' = 0.05$ $\gamma_4' = 0.94$

Eutro = eutrophication category; PDU = primary contact recreation category; Secchi = Secchi depth; TP = total phosphorus; Chla = chlorophyll a; TIN = total inorganic nitrogen

The  $\beta$  and  $\gamma$  indicate unstandardized model coefficients;  $\beta'$  and  $\gamma'$  are standardized model coefficients.

**Table 10: Structural Equation Model Test Statistics for Primary Contact Recreation**

<b>Primary Contact Recreation Models</b>	Coastal Natural Lakes	Coastal Non-natural Lakes	Southeastern Plains	Piedmont	Blue Ridge	North Carolina
Eutro = $\beta_1$ Secchi DU = $\gamma_1$ Eutro	$\chi^2 = 2.95$ ; df = 1 <b>p-value = 0.09</b> <b>AIC = 61.8</b> <b>BIC = 54.2</b>	$\chi^2 = 0.14$ ; df = 1 <b>p-value = 0.71</b> <b>AIC = 43.9</b> <b>BIC = 36.3</b>	$\chi^2 = 1.87$ ; df = 1 <b>p-value = 0.17</b> <b>AIC = 573.4</b> <b>BIC = 571.2</b>	$\chi^2 = 96.$ ; df = 1 p-value = 0.00 AIC = 259.9 BIC = 257.7	$\chi^2 = 1.88$ ; df = 1 <b>p-value = 0.17</b> <b>AIC = 292.8</b> <b>BIC = 290.6</b>	$\chi^2 = 72.2$ ; df = 1 p-value = 0.00 AIC = 124.6 BIC = 119.6
Eutro = $\beta_1$ TP DU = $\gamma_1$ Eutro	$\chi^2 = 0.06$ ; df = 1 <b>p-value = 0.80</b> <b>AIC = 69.3</b> <b>BIC = 61.8</b>	$\chi^2 = 7.20$ ; df = 1 p-value = 0.00 AIC = 43.4 BIC = 35.9	$\chi^2 = 5.78$ ; df = 1 p-value = 0.02 AIC = 611.6 BIC = 609.5	$\chi^2 = 0.09$ ; df = 1 <b>p-value = 0.77</b> <b>AIC = 327.4</b> <b>BIC = 325.2</b>	$\chi^2 = 3.80$ ; df = 1 <b>p-value = 0.05</b> <b>AIC = 275.2</b> <b>BIC = 273.0</b>	$\chi^2 = 0.19$ ; df = 1 <b>p-value = 0.67</b> <b>AIC = 137.9</b> <b>BIC = 133.0</b>
Eutro = $\beta_1$ Chla DU = $\gamma_1$ Eutro	$\chi^2 = 3.36$ ; df = 1 <b>p-value = 0.07</b> AIC = 78.5 BIC = 71.0	$\chi^2 = 0.92$ ; df = 1 <b>p-value = 0.33</b> <b>AIC = 45.3</b> <b>BIC = 37.8</b>	$\chi^2 = 0.03$ ; df = 1 <b>p-value = 0.86</b> <b>AIC = 1193.5</b> <b>BIC = 1191.3</b>	$\chi^2 = 4.25$ ; df = 1 p-value = 0.04 AIC = 334.0 BIC = 331.8	$\chi^2 = 0.94$ ; df = 1 <b>p-value = 0.33</b> AIC = 326.4 BIC = 324.2	$\chi^2 = 9.22$ ; df = 1 p-value = 0.00 AIC = 161.6 BIC = 156.7
Eutro = $\beta_1$ TP + $\beta_2$ Chla DU = $\gamma$ Eutro	$\chi^2 = 4.38$ ; df = 2 <b>p-value = 0.11</b> AIC = 95.2 BIC = 85.8	$\chi^2 = 7.23$ ; df = 2 p-value = 0.03 AIC = 39.3 BIC = 29.9	$\chi^2 = 11.0$ ; df = 2 p-value = 0.00 AIC = 1381.1 BIC = 1378.4	$\chi^2 = 6.66$ ; df = 2 p-value = 0.04 AIC = 347.2 BIC = 344.4	$\chi^2 = 8.93$ ; df = 2 <b>p-value = 0.01</b> AIC = 315.4 BIC = 312.6	$\chi^2 = 17.7$ ; df = 2 p-value = 0.00 AIC = 160.5 BIC = 154.3
Chla = $\beta_1$ TP + $\beta_2$ TIN Eutro = $\gamma_1$ Chla + $\gamma_2$ TP + $\gamma_3$ TIN DU = $\gamma_4$ Eutro	$\chi^2 = 19.2$ ; df = 2 p-value = 0.00 AIC = 115.5 BIC = 98.6	$\chi^2 = 10.3$ ; df = 3 p-value = 0.02 AIC = 77.1 BIC = 60.2	$\chi^2 = 11.0$ ; df = 2 p-value = 0.01 AIC = 1432.4 BIC = 1427.5	$\chi^2 = 6.85$ ; df = 3 <b>p-value = 0.08</b> <b>AIC = 460.2</b> <b>BIC = 455.3</b>	$\chi^2 = 10.8$ ; df = 3 p-value = 0.01 AIC = 438.5 BIC = 433.6	$\chi^2 = 23.4$ ; df = 3 p-value = 0.00 AIC = 216.6 BIC = 205.5

Eutro = eutrophication category; PDU = primary contact recreation category; Secchi = Secchi depth; TP = total phosphorus; Chla = chlorophyll a; TIN = total inorganic nitrogen

The p-values in bold indicate satisfactory (nonsignificant) models (p-values > 0.05). The AIC and BIC values in bold indicate the top one or two models (smaller values more desirable) in an ecoregion.

**Table 11: Structural Equation Models for Secondary Contact Recreation**

<b>Secondary Contact Recreation Models</b>	<b>Coastal Natural Lakes</b>	<b>Coastal Non-natural Lakes</b>	<b>Southeastern Plains</b>	<b>Piedmont</b>	<b>Blue Ridge</b>	<b>North Carolina</b>
<b>Model AS</b>						
Eutro = $\beta_1$ Secchi	$\beta_1' = -0.59$	$\beta_1' = -0.67$	$\beta_1' = -0.53$	$\beta_1' = -0.74$	$\beta_1' = -0.89$	$\beta_1' = -0.63$
DU = $\gamma_1$ Eutro	$\gamma_1' = 0.31$	$\gamma_1' = 0.05$	$\gamma_1' = 0.85$	$\gamma_1' = 0.95$	$\gamma_1' = 0.89$	$\gamma_1' = 0.93$
<b>Model BS</b>						
Eutro = $\beta_1$ TP	$\beta_1' = 0.39$	$\beta_1' = 0.72$	$B_1' = -0.07$	$\beta_1' = 0.67$	$\beta_1' = 0.62$	$\beta_1' = 0.60$
DU = $\gamma_1$ Eutro	$\gamma_1' = 0.31$	$\gamma_1' = 0.05$	$\gamma_1' = 0.85$	$\gamma_1' = 0.95$	$\gamma_1' = 0.94$	$\gamma_1' = 0.93$
<b>Model CS</b>						
Eutro = $\beta_1$ Chla	$\beta_1' = 0.65$	$\beta_1' = 0.03$	$B_1' = 0.46$	$\beta_1' = 0.73$	$\beta_1' = 0.66$	$\beta_1' = 0.69$
DU = $\gamma_1$ Eutro	$\gamma_1' = 0.31$	$\gamma_1' = 0.05$	$\gamma_1' = 0.85$	$\gamma_1' = 0.95$	$\gamma_1' = 0.94$	$\gamma_1' = 0.93$
<b>Model DS</b>						
Eutro = $\beta_1$ TP + $\beta_2$ Chla	$\beta_1' = 0.39$	$\beta_1' = 0.79$	$B_1' = -0.44$	$\beta_1' = 0.53$	$\beta_1' = 0.55$	$\beta_1' = 0.55$
	$\beta_2' = 0.65$	$\beta_2' = 0.25$	$\beta_2' = 0.69$	$\beta_2' = 0.60$	$\beta_2' = 0.59$	$\beta_2' = 0.65$
DU = $\gamma$ Eutro	$\gamma_1' = 0.31$	$\gamma_1' = 0.05$	$\gamma_1' = 0.85$	$\gamma_1' = 0.95$	$\gamma_1' = 0.94$	$\gamma_1' = 0.93$
<b>Model ES</b>						
Chla = $\beta_1$ TP + $\beta_2$ TIN	$\beta_1' = 0.17$	$\beta_1' = -0.15$	$B_1' = 0.46$	$\beta_1' = 0.26$	$\beta_1' = 0.25$	$\beta_1' = 0.17$
	$\beta_2' = -0.54$	$\beta_2' = -0.39$	$\beta_2' = 0.08$	$\beta_2' = -0.03$	$\beta_2' = -0.36$	$\beta_2' = -0.25$
Eutro = $\gamma_1$ Chla + $\gamma_2$ TP + $\gamma_3$	$\gamma_1' = 0.73$	$\gamma_1' = 0.23$	$\gamma_1' = 0.71$	$\gamma_1' = 0.61$	$\gamma_1' = 0.61$	$\gamma_1' = 0.66$
TIN	$\gamma_2' = 0.33$	$\gamma_2' = 0.80$	$\gamma_2' = 0.12$	$\gamma_2' = 0.48$	$\gamma_2' = 0.53$	$\gamma_2' = 0.53$
DU = $\gamma_4$ Eutro	$\gamma_3' = 0.17$	$\gamma_3' = -0.05$	$\gamma_3' = -0.62$	$\gamma_3' = 0.10$	$\gamma_3' = 0.06$	$\gamma_3' = 0.05$
	$\gamma_4' = 0.31$	$\gamma_4' = 0.05$	$\gamma_4' = 0.85$	$\gamma_4' = 0.95$	$\gamma_4' = 0.94$	$\gamma_4' = 0.93$
Eutro = eutrophication category; PDU = primary contact recreation category; Secchi = Secchi depth; TP = total phosphorus; Chla = chlorophyll a; TIN = total inorganic nitrogen						

The  $\beta$  and  $\gamma$  indicate unstandardized model coefficients;  $\beta'$  and  $\gamma'$  are standardized model coefficients.

**Table 12: Structural Equation Models Test Statistics for Secondary Contact Recreation**

<b>Secondary Contact Recreation Models</b>	Coastal Natural Lakes	Coastal Non-natural Lakes	Southeastern Plains	Piedmont	Blue Ridge	North Carolina
Eutro = $\beta_1$ Secchi DU = $\gamma_1$ Eutro	$\chi^2 = 0.73$ ; df = 1 <b>p-value = 0.39</b> <b>AIC = 80.4</b> <b>BIC = 72.9</b>	$\chi^2 = 1.07$ ; df = 1 <b>p-value = 0.30</b> <b>AIC = 72.7</b> <b>BIC = 65.1</b>	$\chi^2 = 2.97$ ; df = 1 <b>p-value = 0.09</b> <b>AIC = 581.3</b> <b>BIC = 579.1</b>	$\chi^2 = 73.1$ ; df = 1 p-value = 0.00 AIC = 246.0 BIC = 243.8	$\chi^2 = 0.40$ ; df = 1 <b>p-value = 0.53</b> <b>AIC = 255.6</b> <b>BIC = 253.4</b>	$\chi^2 = 58.0$ ; df = 1 p-value = 0.00 AIC = 115.4 BIC = 110.5
Eutro = $\beta_1$ TP DU = $\gamma_1$ Eutro	$\chi^2 = 0.18$ ; df = 1 <b>p-value = 0.67</b> <b>AIC = 87.9</b> <b>BIC = 80.4</b>	$\chi^2 = 0.06$ ; df = 1 p-value = 0.81 AIC = 72.3 BIC = 64.7	$\chi^2 = 4.54$ ; df = 1 p-value = 0.03 AIC = 619.5 BIC = 617.3	$\chi^2 = 3.69$ ; df = 1 <b>p-value = 0.05</b> <b>AIC = 313.5</b> <b>BIC = 311.3</b>	$\chi^2 = 5.31$ ; df = 1 <b>p-value = 0.02</b> <b>AIC = 262.1</b> <b>BIC = 259.9</b>	$\chi^2 = 0.00$ ; df = 1 <b>p-value = 0.97</b> <b>AIC = 128.8</b> <b>BIC = 123.9</b>
Eutro = $\beta_1$ Chla DU = $\gamma_1$ Eutro	$\chi^2 = 0.10$ ; df = 1 <b>p-value = 0.75</b> AIC = 97.2 BIC = 89.7	$\chi^2 = 1.65$ ; df = 1 <b>p-value = 0.20</b> <b>AIC = 74.1</b> <b>BIC = 66.6</b>	$\chi^2 = 0.04$ ; df = 1 <b>p-value = 0.84</b> <b>AIC = 1201.4</b> <b>BIC = 1199.2</b>	$\chi^2 = 15.6$ ; df = 1 p-value = 0.00 AIC = 320.1 BIC = 317.9	$\chi^2 = 0.64$ ; df = 1 <b>p-value = 0.42</b> AIC = 313.3 BIC = 311.1	$\chi^2 = 15.6$ ; df = 1 p-value = 0.00 AIC = 152.5 BIC = 147.6
Eutro = $\beta_1$ TP + $\beta_2$ Chla DU = $\gamma$ Eutro	$\chi^2 = 0.43$ ; df = 2 <b>p-value = 0.81</b> AIC = 113.8 BIC = 104.4	$\chi^2 = 1.76$ ; df = 2 p-value = 0.41 AIC = 68.1 BIC = 58.7	$\chi^2 = 8.89$ ; df = 2 p-value = 0.02 AIC = 1389.0 BIC = 1386.3	$\chi^2 = 15.6$ ; df = 2 p-value = 0.00 AIC = 333.3 BIC = 330.5	$\chi^2 = 10.5$ ; df = 2 <b>p-value = 0.01</b> AIC = 302.3 BIC = 299.5	$\chi^2 = 24.9$ ; df = 2 p-value = 0.00 AIC = 151.4 BIC = 145.2
Chla = $\beta_1$ TP + $\beta_2$ TIN Eutro = $\gamma_1$ Chla + $\gamma_2$ TP + $\gamma_3$ TIN DU = $\gamma_4$ Eutro	$\chi^2 = 19.2$ ; df = 2 p-value = 0.85 AIC = BIC =	$\chi^2 = 1.89$ ; df = 3 p-value = 0.60 AIC = 105.9 BIC = 89.0	$\chi^2 = 8.96$ ; df = 2 p-value = 0.03 AIC = 1440.3 BIC = 1435.4	$\chi^2 = 17.4$ ; df = 3 <b>p-value = 0.00</b> <b>AIC = 446.3</b> <b>BIC = 441.3</b>	$\chi^2 = 14.8$ ; df = 3 p-value = 0.00 AIC = 425.4 BIC = 420.4	$\chi^2 = 27.3$ ; df = 3 p-value = 0.00 AIC = 207.5 BIC = 196.4

Eutro = eutrophication category; PDU = primary contact recreation category; Secchi = Secchi depth; TP = total phosphorus; Chla = chlorophyll a; TIN = total inorganic nitrogen

The p-values in bold indicate satisfactory (nonsignificant) models (p-values > 0.05). The AIC and BIC values in bold indicate the top one or two models (smaller values more desirable) in an ecoregion.

For secondary contact recreation (Tables 10 and 12), the results were similar. There was no model that surpassed the other models, because there was not one model that was nonsignificant at the  $p > 0.05$  for all ecoregions and the entire state (nonnatural lakes), but we were able to use AIC and BIC to compare the models' performance (Table 12). Considering only the models with nonsignificant p-values, the models with the best AIC and BIC values were the AS and BS models. Similar to primary contact recreation, the AS model uses a single water quality indicator of Secchi depth and the BS model uses only total phosphorus. For reasons similar to what was discussed previously, the AS model is a less desirable choice. Additionally, if we consider acceptable models to be those with  $p > 0.01$ , then model BS would have nonsignificant models in all the ecoregions and in the entire state. Finally, for both primary contact recreation and secondary contact recreation the models CP and CS, which used chlorophyll a as the predictor also performed satisfactorily, but not as well as the AP/AS and BP/BS models.

Considering the suite of models for both primary and secondary contact recreation (Tables 9 and 10), there was little to no difference in the choice of water quality criteria variables for the different ecoregions. Considering both the structural equation modeling results and the between region expert correlations (Tables 10 and 11), the results indicate that there is no justification for choosing different criterion variables in different ecoregions. Therefore, in North Carolina lakes and reservoirs, a statewide

nutrient criterion variable would sufficiently predict eutrophication-related impairments of the designated use.

### **4.5.3 Multiple Regression (MR)**

We used multiple regression (MR) to model eutrophication and then to separately model designated use attainment. We developed these models to assess whether we needed to directly model designated use or whether modeling eutrophication would provide us the information we needed to determine the most appropriate nutrient criteria variables. We were also able to determine if there were any ecoregional differences that would confirm the USEPA's recommendation for developing regional standards or whether a statewide standard would provide equivalent results.

MR is a linear modeling method that considers the relationship between several independent or predictor variables and a single dependent variable (Reckhow and Chapra 1983). MR has been successfully used to describe relationships between eutrophication causal variables, such as phosphorus and nitrogen, and response variables, such as chlorophyll and Secchi depth, in multiple regions throughout the U.S. (Novotny and Olem 1994). In this article we are using MR to (1) determine the water quality variables that are most predictive of eutrophication or trophic status, and (2) to determine whether or not the most predictive variables of eutrophication are also the

most predictive variables of the designated uses. The MR equations used to examine the direct effects of the predictive water quality variables on eutrophication and the direct effects of the water quality variables and eutrophication on the designated use category are

$$Eutro = \alpha + X B \quad (2)$$

and

$$DU = \alpha' + X B' + \beta' Eutro , \quad (3)$$

where Eutro is the eutrophication category (expert elicitation data),  $\alpha$  is the model intercept, X is a matrix of the water quality variables, B is a vector of the model coefficients,  $\beta$  is the model coefficient for Eutro, and DU is the designated use category for either primary contact recreation or secondary contact recreation (expert elicitation data). The models were created for each ecoregion and the entire state; therefore, the MR may differ if there are different water quality variables that are better predictors in some regions and not others. Additionally, it is important to note that in equation 3 the variable Eutro is a data vector assessed from the experts, not a vector of predicted values.

Several water quality variables were log<sub>10</sub> transformed; these variables included total nitrogen, total inorganic nitrogen, total phosphorus, chlorophyll a, and turbidity. Dissolved oxygen and Secchi depth, on the other hand, remained in their original units. The variables were transformed to minimize the influence of leverage points. Additionally, for the eutrophication and the designated use categories, we used the average expert response for each ecoregion.

#### **4.5.4 Multiple Regression Modeling (MR) Results**

We created MR for each of the ecoregions. In these models we linked the water quality variables to the eutrophication category and secondly we linked the water quality variables and eutrophication to the designated uses categories. The models were created this way so that we could determine whether we needed to explicitly model designated use attainment or whether modeling eutrophication solely would provide us equivalent results. We were also able to assess if there were ecoregional differences or not.

There was not a single model that we used in all the ecoregions; instead we developed parsimonious MR models for each ecoregion individually and then compared the results across ecoregions. Additionally, our models were chosen using Mallows' CP; smaller values indicated better models. We believe that the model

coefficients more accurately predict the average category of eutrophication, primary contact recreation, or secondary contact recreation.

Comparing the MR models across the different ecoregions, the models are not exactly the same (Table 13). Even though these models do not provide identical stories, there are certain variables that are consistently predictive in all of the models in all of the ecoregions. For the Eutrophication MR, chlorophyll a and then total phosphorus were the most predictive variable in all the ecoregions. Though there were other variables, such as total inorganic nitrogen or turbidity that were important in certain MR models in some ecoregions, these variables were not consistently predictive of the average eutrophication category.

The models include a standardized coefficient, the standard error of the coefficient (in parentheses), and the adjusted  $R^2$  value. For primary contact recreation and secondary contact recreation, the eutrophication category elicited from the experts fully or partially mediates for these designated uses. All of the models produced adjusted  $R^2$  values above 0.45 for eutrophication and primary contact recreation; the models for secondary contact recreation had adjusted  $R^2$  values that ranged from 0.16 to 0.85.

We also used MR to link primary contact recreation and secondary contact recreation to the water quality variables and the average expert assessment of eutrophication (Table 13). In both models the designated uses, primary contact

recreation and secondary contact recreation, were partially mediated by eutrophication (Baron and Kenny 1986). Since eutrophication partially mediates for both of the designated uses, if we can predict eutrophication, then it tells us almost everything that we need to know about the designated use category. As a result, the water quality variable(s) that are most predictive of eutrophication will also be the best indicators of the designated use category.

**Table 13: Multiple Regression Results for Eutrophication, Primary Contact Recreation, and Secondary Contact Recreation for all the ecoregions in North Carolina**

<b>Ecoregions</b>	<b>Eutrophication</b> Eutro = $\alpha$ + X B	<b>Primary Contact Recreation</b> PDU = $\alpha$ + X B + $\beta$ Eutro	<b>Secondary Contact Recreation</b> SDU = $\alpha$ + X B + $\beta$ Eutro
Coastal Natural Lakes	$\text{Eutro} = 3.11 + 0.39 \text{ TIN} + 0.80 \text{ TP} + 0.97 \text{ Chla} - 0.13 \text{ Secchi}$ <p>(0.30) (0.16) (0.19) (0.11) (0.06)</p> Adjusted R <sup>2</sup> = 0.50	$\text{PDU} = 0.51 - 0.12 \text{ Secchi} + 0.83 \text{ Eutro}$ <p>(0.19) (0.06) (0.06)</p> Adjusted R <sup>2</sup> = 0.61	$\text{SDU} = 1.26 + 0.45 \text{ Eutro}$ <p>(0.21) (0.08)</p> Adjusted R <sup>2</sup> = 0.16
Coastal Nonnatural Lakes	$\text{Eutro} = 2.64 + 0.36 \text{ TIN} + 1.23 \text{ TP} + 0.87 \text{ Chla} + 0.12 \text{ DO} + 0.34 \text{ Turb}$ <p>(0.42) (0.15) (0.20) (0.13) (0.04) (0.17)</p> Adjusted R <sup>2</sup> = 0.46	$\text{PDU} = 0.38 + 0.80 \text{ Eutro}$ <p>(0.18) (0.06)</p> Adjusted R <sup>2</sup> = 0.50	$\text{SDU} = 1.11 - 0.33 \text{ Chla} + 0.66 \text{ Eutro}$ <p>(0.21) (0.15) (0.07)</p> Adjusted R <sup>2</sup> = 0.35
Southeastern Plains	$\text{Eutro} = 2.00 + 1.04 \text{ Chla} - 0.27 \text{ Secchi} + 0.31 \text{ Turb}$ <p>(0.15) (0.08) (0.05) (0.13)</p> Adjusted R <sup>2</sup> = 0.82	$\text{PDU} = 1.11 - 0.46 \text{ Secchi} + 0.82 \text{ Eutro}$ <p>(0.28) (0.06) (0.07)</p> Adjusted R <sup>2</sup> = 0.82	$\text{SDU} = 0.76 - 0.47 \text{ Secchi} + 0.25 \text{ Turb} + 0.76 \text{ Eutro}$ <p>(0.27) (0.07) (0.16) (0.08)</p> Adjusted R <sup>2</sup> = 0.85
Piedmont	$\text{Eutro} = 2.76 + 0.17 \text{ TIN} + 0.57 \text{ TP} + 0.98 \text{ Chla} - 0.20 \text{ Secchi} + 0.33 \text{ Turb}$ <p>(0.19) (0.07) (0.10) (0.07) (0.04) (0.10)</p> Adjusted R <sup>2</sup> = 0.58	$\text{PDU} = 1.02 + 0.11 \text{ TIN} + 0.37 \text{ Chla} - 0.36 \text{ Secchi} + 0.43 \text{ Turb} + 0.57 \text{ Eutro}$ <p>(0.12) (0.04) (0.06) (0.03) (0.07) (0.03)</p> Adjusted R <sup>2</sup> = 0.84	$\text{SDU} = 1.82 + 0.21 \text{ TIN} + 0.24 \text{ TP} + 0.29 \text{ Chla} + 0.04 \text{ DO} - 0.26 \text{ Secchi} + 0.38 \text{ Turb} + 0.29 \text{ Eutro}$ <p>(0.24) (0.06) (0.10) (0.08) (0.02) (0.04) (0.10) (0.04)</p> Adjusted R <sup>2</sup> = 0.61
Blue Ridge	$\text{Eutro} = 3.31 + 0.55 \text{ TN} + 0.66 \text{ TP} + 0.71 \text{ Chla} - 0.16 \text{ Secchi} + 0.39 \text{ Turb}$ <p>(0.21) (0.16) (0.12) (0.09) (0.04) (0.12)</p> Adjusted R <sup>2</sup> = 0.63	$\text{PDU} = -0.83 - 0.11 \text{ TIN} - 0.40 \text{ TP} - 0.31 \text{ Chla} - 0.06 \text{ DO} + 1.31 \text{ Eutro}$ <p>(0.32) (0.08) (0.13) (0.11) (0.02) (0.06)</p> Adjusted R <sup>2</sup> = 0.77	$\text{SDU} = -1.47 - 0.54 \text{ TP} + 1.13 \text{ Eutro}$ <p>(0.50) (0.22) (0.08)</p> Adjusted R <sup>2</sup> = 0.47

Eutro = eutrophication category; PDU = primary contact recreation category; SDU = secondary contact recreation category; Secchi = Secchi depth; TP = total phosphorus; Chla = chlorophyll a; TN = total nitrogen; Turb = turbidity

#### **4.5.5 Binomial Regression Model (BRM)**

The binomial regression model (BRM) was designed to predict a distribution over eutrophication categories from a given water quality characteristic profile. As a result, the BRM, unlike SEM and MR, predicts the probability of being in a particular eutrophication category, or the average distribution over the eutrophication categories (for example, values provided as category 1 = 0, category 2 = 0.2, category 3 = 0.5, category 4 = 0.3, and category 5 = 0), instead of a single value average of the eutrophication category (for example, average category = 2.5).

Using the previous results, we made two assumptions with this model. First, we chose to develop a statewide model to predict the eutrophication category, since we assumed that there were nonsignificant ecoregional differences (expert elicitation results and SEM and MR model results). Second, we assumed that if we could determine which variables were most predictive of eutrophication, these variables would also be the most predictive of the designated uses (MR results); therefore, the model predicts the eutrophication status, not the designated use status.

The model was parameterized with two types of data: water quality data and expert elicitation data. We used untransformed water quality data, since the untransformed data best fit our model and its assumptions. Also, we used the expert judgments provided during the elicitation to quantify the eutrophication status; these judgments were provided as a distribution over the five categories for each of the rows

of water quality data (i.e. For the five categories an expert could provide a probability of being in each of the five eutrophication categories; the sum of the probabilities for all five categories adds to 1).

To minimize expert-specific bias in the assessment of the distributions across eutrophication categories, we first averaged the eutrophication distributions among all experts, i.e.

$$\pi_i = \frac{\sum_{k=0}^m \pi_{ik}}{m}, \quad (4)$$

where  $\pi_{ik}$  is expert  $k$ 's assessment of the probability of the eutrophication status being in category  $i$  and  $m$  is the number (14) of experts in this study. Equation 4 provides us with the average distribution over the eutrophication categories for each of the 100 data rows (data described in Section 4.3).

Using the average distributions over eutrophication categories (equation 4), we then extracted the mean probability for each such distribution by calculating the expected value of the distribution and dividing by the number of eutrophication categories

$$p' = \frac{\sum_{i=0}^n i * \pi_i}{n}, \quad (5)$$

where  $p'$  is the mean probability,  $i$  is the eutrophication category,  $\pi$  is the average distribution over eutrophication categories, and  $n$  is the total number of eutrophication categories (i.e.,  $i = 0, 1, 2, 3, 4$ , for a total of 5 eutrophication categories; for the binomial distribution,  $n = 4$ ).

A useful property of the binomial distribution is that it is fully characterized by the variables  $p'$  and  $n$ . Since  $n$  is fixed at 4, each expert distribution over eutrophication categories,  $\pi$ , can be characterized and reconstructed from the predicted values of  $p'$  alone. In other words, for a given value of  $p'$ , the probability in eutrophication category,  $i$ , is determined from

$$P(X = i) = \frac{n!}{i!(n-i)!} p'^i (1-p')^{n-i}. \quad (6)$$

Using equation 6, we can estimate the conditional probabilities for each eutrophication category.

Taking advantage of the preceding facts, we regress the predicted  $p'$  against all the water quality variables

$$p' = \alpha + X\Gamma , \quad (7)$$

where  $X$  is the matrix of water quality variables and  $\Gamma$  is the vector of regression coefficients. Combining the binomial model with regression allowed us to generate a distribution of eutrophication categories from a given profile of water quality characteristics. Applying this procedure many times using Monte Carlo simulation, the model was able to provide distributions over the range of water quality conditions.

#### **4.5.6 Binomial Regression Modeling (BRM) Results**

The final regression equation for  $p'$ , the prediction of the weighted average of the eutrophication categories, with standardized coefficients, is

$$p' = 0.013 TN + 0.008 TIN + 0.062 TP + 0.119 Chla + 0.013 DO - 0.055 Secchi + 0.028 Turb . \quad (8)$$

Combining the prediction of  $p'$  from the regression model (equation 8) with the binomial distribution (equation 6) provides the distribution over the eutrophication categories.

As Figure 9 indicates, our model fits quite well. The probabilities extracted from the binomial distribution,  $p'$ , versus the fitted binomial probabilities fall close to the 1-1 line (Figure 9b). Additionally, there is no discernable pattern in the plot of the residuals (Figure 9a), again supporting our claim of good model fit.

If the model was perfect with respect to the average distributions over eutrophication categories, then plots of the predicted probabilities for a given category versus the actual probabilities for the category would be along the 45 degree line. The actual comparisons of such values are shown in Figure 10. While not perfect, the model clearly has a large degree of predictive power. In fact, the root mean squared error (RMSE) for the regression indicates that our model predicts quite well ( $\mu = 4.05$ , maximum = 7.59, minimum = 0.57). Additionally, we conducted a jackknife analysis to test the accuracy of the BRM. By calculating the error between the jackknife estimate and  $z$ , the extracted probability from the average distributions of eutrophication categories, we were able to verify the good performance of the BRM (average RMSE = 0.07).

In this model, we included all the variables because the experts were presented all these variables during the elicitation. If the experts were able to accurately articulate

their judgment processes then those variables that were used the least to assess eutrophication would be the least predictive variables; similarly, the variables that were the most informative of the eutrophication status would be the most predictive.

The most predictive variable in the BRM is chlorophyll a. The next most predictive variables are total phosphorus and Secchi depth, respectively. These predictive variables are indicators of trophic status. Increased chlorophyll a levels indicate an algal response due to more eutrophic conditions. Additionally, total phosphorus represents the primary nutrient causal variable in these systems, since it is widely accepted that lakes in the mid-Atlantic region are phosphorus limited. Finally, decreased Secchi depth is indicative of reduced water clarity, which is a response that occurs in more eutrophic waters.

Using the prediction of  $p'$  in the binomial distribution provided estimates of the distribution over the eutrophication categories. The use of this model is supported by Figure 11. The pattern displayed in the simulated BRM (Figure 11a) is similar to the pattern demonstrated in the data from the expert elicitations. Therefore the use of the BRM provides a fairly accurate prediction of the probability of being in one of the five eutrophication categories.

Figure 9: Plots of the Residuals versus Extracted Binomial Probabilities and the Fitted Binomial Probabilities versus Extracted Binomial Probabilities

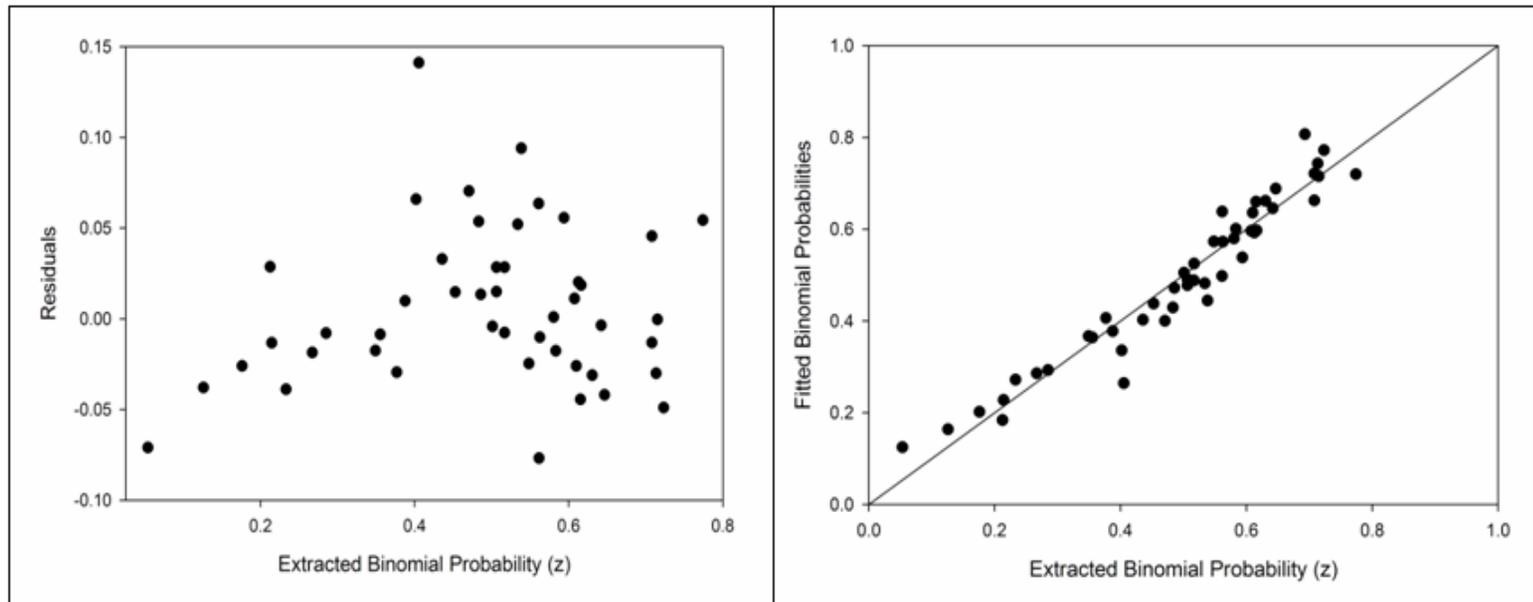
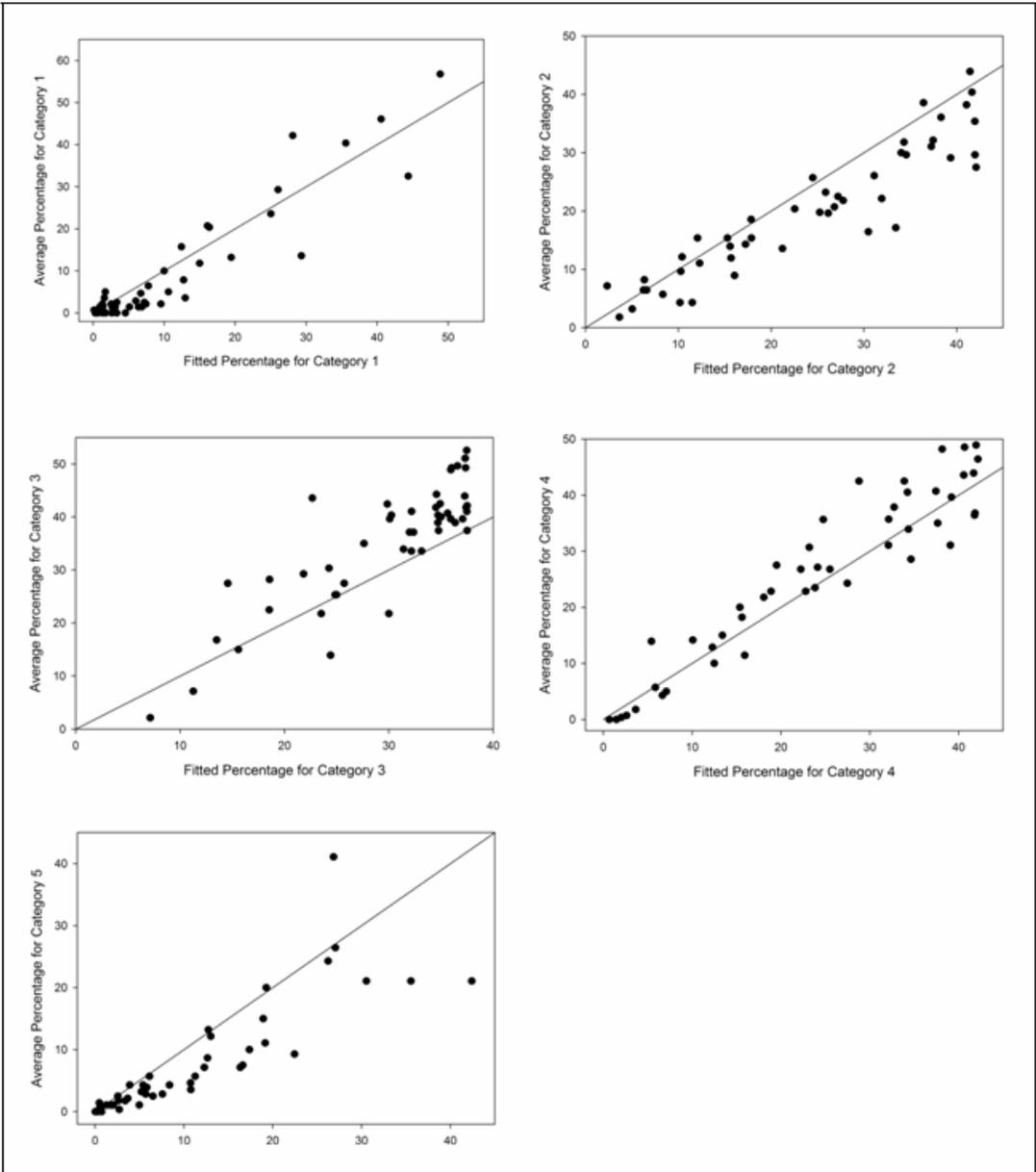
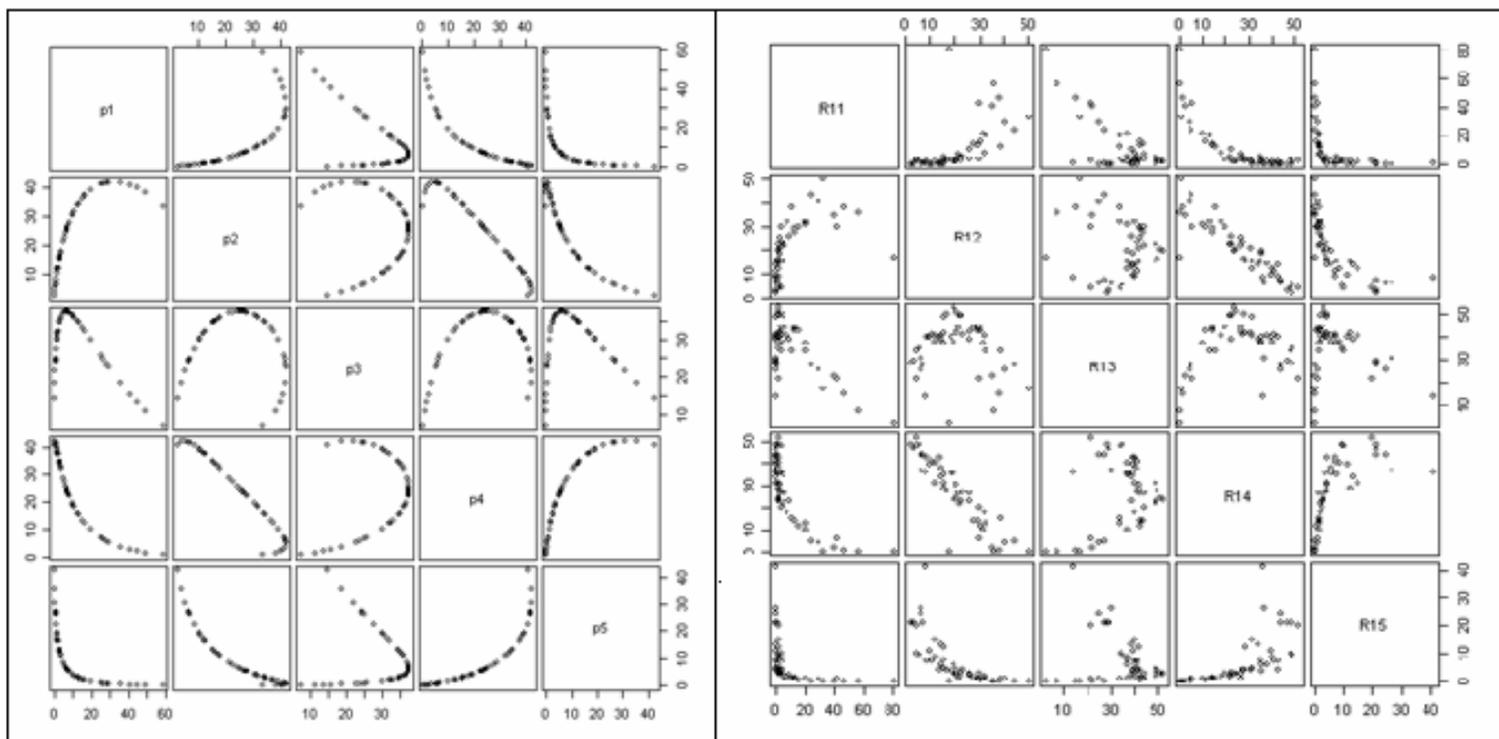


Figure 10: Plots of Average Percentage for Each Category from Experts versus Fitted Percentage for each Category using the Binomial Regression Model



The line indicates the 1 to 1 line; if the model was a perfect predictor of the expert responses, then the results would perfectly match the line.

Figure 11: Scatterplots of (a) Distributions Generated using Binomial Multiple Regression Modeling, and (b) Average Distributions over 14 Experts for each of the 48 Shared Eutrophication Profiles



## **4.6 Discussion**

### **4.6.1 Predictive Nutrient Criteria Results**

These models demonstrated the difficulty of creating models for nutrient criteria. Since eutrophication conditions are dynamic and can show a great deal of natural variability within an ecoregion, the systems do not demonstrate a traditional “threshold” effect. As a result, it is extremely difficult to determine the appropriate nutrient criteria water quality variable and level. And it is even harder when that decision must be substantively linked to the designated use. Therefore, to address the issue of choosing nutrient criterion variable(s) that are linked to the designated use, we used three statistical approaches: structural equation modeling (SEM), multiple regression (MR), and binomial multiple regression (BRM).

### **4.6.2 Structural Equation Modeling (SEM)**

SEMs were developed for each ecoregion. Within each ecoregion there were several models that were plausible representations of the relationship between the eutrophication conditions and the designated uses. Since there were competing models, we used model fit indices to help indicate how well each model performed in comparison to the other models. Using these indices, there was not one model that outperformed the others in all the ecoregions. Our models did indicate, however, that

for both primary contact recreation and secondary contact recreation the most predictive nutrient criteria variables were total phosphorus, Secchi depth, and chlorophyll a.

We were disappointed that the nonsignificant models did not take advantage of the full features of SEM. Ideally, we would have been able to represent the eutrophication causal chain, using the measured water quality variables. Instead, there were difficulties, unlike in previous studies, largely because of the modification in the methods to collect expert elicitation data on eutrophication and the designated uses. As a result of explicitly including eutrophication status in our SEMs, the measured water quality variables became significantly less important in predicting the designated use.

#### **4.6.3 Multiple Regression (MR)**

The MR models were developed for each of the ecoregions. In these models we linked the water quality variables to the eutrophication category and secondly we linked the water quality variables and eutrophication to the designated uses categories.

Developing the models in this fashion allowed us to assess which variables were most predictive, whether there were ecoregional differences, and whether it was necessary to explicitly model designated use attainment.

The MR models indicated that chlorophyll a and secondly turbidity were the most predictive variables for eutrophication. In describing eutrophication conditions, both chlorophyll a and turbidity are response variables and better represent the effects

of nitrogen and phosphorus pollution. It was somewhat surprising that turbidity was important in these models. In North Carolina much of the turbidity is sediment and not algal-induced. As a result, it is not necessarily a good indicator of eutrophication status, unless it is representative of light limitation.

For the designated use MR models, eutrophication was the most predictive variable. For the designated use MR models, the eutrophication category fully mediated for the Coastal Plain (both natural and nonnatural lakes) and Blue Ridge ecoregions; it partially mediated for the Southeastern Plains and Piedmont ecoregions. Because the majority of the lakes and reservoirs in North Carolina are located in the Piedmont and Southeastern Plains, there is greater natural variability between lakes which may be the reason eutrophication partially, and not fully, mediates for the designated uses.

Additionally, in the Piedmont and Southeastern Plains, the chief variables that were predictive for the designated use MR models, other than the eutrophication category, were Secchi depth and turbidity. The additions of these variables in the model possibly reflect the effect of aesthetics on designated use attainment.

#### **4.6.4 Binomial Regression Model (BRM)**

The BRM predicts the probability distribution over the five eutrophication categories. Using the results from the other models, we choose to develop a statewide model to predict the eutrophication category. We assumed that there were

nonsignificant ecoregional differences and that if we could determine which variables were most predictive of eutrophication, these variables would also be the most predictive of the designated uses.

The BRM results indicated that chlorophyll a, then total phosphorus, and third Secchi depth are the most predictive variables of the eutrophication category. The results of the BRM supported what the experts stated during part 2 of the expert elicitation; the measured water quality variables that they felt were most important for making their assessment of the eutrophication category were chlorophyll a, total phosphorus, and Secchi depth.

#### **4.6.5 Comparison of Model Results**

All the models indicated that chlorophyll a was one of the most predictive variables. There were other variables that were predictive, though not in all the models; these variables included total phosphorus, Secchi depth, and turbidity. It is not surprising that chlorophyll a was one of the most predictive variables. Since chlorophyll a is an indicator of algal response to eutrophication conditions, it represents a variable that is more closely linked to eutrophication conditions, which would trigger a waterbody to be classified as impaired. Considering the other predictive variables, total phosphorus represents the limiting nutrient in the system and Secchi depth and turbidity are water clarity indicators.

The role of Secchi depth and turbidity could use further clarification. Secchi depth and turbidity measurements are affected by both algal growth and sediment loading; however in North Carolina, the water clarity problems in lakes and reservoirs are largely attributed to sedimentation. It has been hypothesized, however, that increased sediment levels affect eutrophication conditions by blocking light that is essential for algal production. Therefore, in North Carolina, the algal growth is not necessarily nutrient limited; instead, algal growth is impeded by light limitation. Additionally, since primary and secondary contact recreation users, in general, desire higher water clarity, it is an appropriate indicator of designated use status; though not a perfect indicator of eutrophication-related impairments of the designated use.

Comparing the three models, the BRM performed the best. Though the SEM and MR models performed adequately, the BRM was able to accurately predict the eutrophication category instead of the average eutrophication category. The BRM performed the best because it was best equipped to handle the water quality and categorical expert data through the use of the binomial distribution.

#### **4.6.6 Multiple Experts**

This paper used multiple experts to assess the eutrophication / trophic category, and the designated use category for two designated uses, primary contact recreation and secondary contact recreation. Since eutrophication conditions manifest themselves

differently in different systems, the use of expert judgments provided us a means of formally assessing the trophic status, and then the experts' beliefs of how both the trophic status and the water quality variables affect the designated use category. These judgments were essential to our statistical models and provided a means to quantitatively justify the choice of one or more of the water quality variables for use as nutrient criteria.

The use of multiple experts allowed us to capture a range of expert judgments and combine those judgments, in a manner appropriate to the statistical model, to represent the "mean expert." Additionally since we had multiple experts in multiple ecoregions we could combine these judgments in one ecoregion or across ecoregion.

#### **4.6.7 Regional versus Statewide Criteria**

The expert judgments and the statistical modeling provided the evidence needed to conclude that there is not a basis for the selection of different water quality variables for nutrient criteria in different ecoregions. Using the expert elicitation correlations we were able to see that there was not a significant difference in the correlations within the same ecoregion and between different ecoregions. Additionally, the models demonstrated that there were not notable differences between the ecoregions that would indicate the need for choosing ecoregional criteria variables. In fact, there were a

number of cases where the same model for both the SEM and MR performed the best in multiple ecoregions.

Finally, considering the predictive water quality variables, there was a consistent story in all the ecoregions of which variables would adequately predict either the eutrophication and/or the designated use categories. Since a statewide criterion is easier to implement than an ecoregion criterion, we are confident for North Carolina that a statewide criterion would perform satisfactorily in nutrient criteria variable selection.

#### **4.6.8 Eutrophication versus Designated Use Models**

Our models demonstrated that if we can determine the most predictive variable or variables for eutrophication, then those variables are an adequate means of determining which variables would best predict designated use attainment. This result is an important advancement in the selection of nutrient criteria variables since previously the only way to explicitly link the nutrient criteria variables to the designated use was through modeling this linkage using water quality data and expert elicitation data on the probability of designated use attainment. Being able to determine the variables that are most important to assess trophic status should ease the implementation of using procedures such as ours to formally evaluate the choice of nutrient criteria variables.

#### **4.6.9 Comparison to Other Methods of Variable Selection**

The method presented in this article is not the only approach used to choose the nutrient criteria variables; the USEPA supports a Ecoregion Reference Waterbody approach (Environmental Protection Agency 2000e) and the current North Carolina nutrient criterion was created using a panel of scientists (Weiss and Kuenzler 2001). The USEPA Ecoregion Reference Waterbody Approach uses four predictive variables, total nitrogen, total phosphorus, chlorophyll a, and Secchi depth, with no emphasis on the choice of one variable over another variable (i.e. the weight on each variable is 0.25). As a result, using this approach a State or Tribe may be regulating criteria variables that do not provide any additional predictive benefit or not placing great enough emphasis on the variables that give us the greatest indication of eutrophication impairments. In contrast, North Carolina's current nutrient criterion variable is chlorophyll a. They choose this variable since it is a response variable that represents a measure of undesirable algal conditions. Because chlorophyll a is a response variable, it is arguably a better predictor of eutrophication and designated use status. Our method, on the other hand, supports the use of statistical models that link the water quality variables to eutrophication and the designated use. As a result, we are able to provide substantial evidence based on predictive relationships to determine which of the variables would serve as the best scientific surrogate to the designated use. Using the models we can determine whether to employ a single criterion variable or multiple criteria variables

and which variable(s) would provide adequate information to assess waterbody impairment.

Using our models, we determined that the majority of evidence supported the use of a chlorophyll a criterion, with evidence that also indicated that total phosphorus and Secchi depth would also be predictive of designated use attainment. These results support the selection of the current North Carolina nutrient criterion variable, which was determined using a scientific panel. These results also indicate which of the variables, supported by the USEPA, would be the best predictors of eutrophication impairments to the designated use.

#### **4.6.10 Future Research Directions**

In this paper we did not focus on the selection of the nutrient criterion levels. This is because the selection of the level is a trade-off between maximizing water quality and minimizing mitigation costs. Since some water quality variables have clear thresholds (example: dissolved oxygen), the trade-off decision is a bit easier. For eutrophication, as discussed earlier, there are not clear thresholds and therefore the determination of the level is more difficult, involving a decision-maker assessing his/her risk of nonattainment of the designated use. The choice of the nutrient criterion level is an important research topic to address in future research, but this paper addressed an

equally important issue in criteria setting: the determination of which variable(s) to choose as the proxy to assess eutrophication-related designated use impairments.

Future research directions, which are well underway, include using the results of these models to assist decision makers in choosing nutrient criteria levels. Since the choice of levels involves trade-offs that are driven by societal choices between maximizing environmental protection and minimizing costs, science should not suggest criteria levels. The decision on where to set a criterion level is difficult and decision-makers need guidance to make an appropriate choice. Thus, the use of techniques such as multiattribute utility analysis (Keeney and Raiffa 1976) show promise as a quantitative means of assisting decision-makers determine the ideal nutrient criterion level.

## ***4.7 Conclusions***

The research presented in this article provides a substantive basis for making a criterion variable selection, one of two important decisions when setting nutrient criteria. There are few waterbodies that have measured the variety of water quality parameters that would be desirable to assess eutrophication. Despite this fact, States and Tribes need answers regarding whether a lake or reservoir is impaired. The choice of whether a waterbody is classified as impaired requires judgments, which should be formally incorporated into the research method. This research expands the use of

predictive statistical models to determine which water quality variables best predict eutrophication-related designated use impairments.

## **5. Choosing Water Quality Impairment Criteria: Using Science and Judgments to Inform Decision-Making**

### **5.1 Introduction**

Many states and tribes are currently struggling with how to set criteria for the number one water pollution problem in lakes and reservoirs, eutrophication. Eutrophication is a condition where excess nutrients can lead to low oxygen levels, noxious algal blooms, and fish kills. Because eutrophication is a condition that manifests itself differently in different systems, no obvious criterion variable with a clear threshold exists that can be used to set the criterion level. Moreover, the choice of the criterion level requires a decision-maker's value trade-offs between the objectives of minimizing cost and maximizing water quality. To address this problem, we have developed a nutrient criteria value model that includes two submodels, a water quality model and a multiattribute value model. The model identifies the best criterion variable to use and the expected value criterion level for that variable. We applied the model to lakes and reservoirs in North Carolina. Based on the model, the criterion variable chosen was total phosphorus. Using the preferences of North Carolina environmental decision-makers, the optimal criterion level for total phosphorus was approximately 0.04 mg/L, and the expected value is relatively insensitive between 0.03 mg/L and 0.07 mg/L. The results of this study demonstrate that a multiattribute value or utility analysis can

be used as a practical approach to selecting nutrient criteria for waterbodies in the United States.

## **5.2 Background**

One of the most vexing environmental policy issues is how to set water quality standards. Sections 101(a) and 303(c) of the Clean Water Act require states to establish water quality standards to protect the nation's waterbodies from excessive impairments. Water quality standards consist of an antidegradation clause, a qualitative designated use, and a qualitative or quantitative criterion. The antidegradation clause is a narrative statement that the designated use cannot be demoted because of degraded water quality conditions. The designated use is a narrative statement that describes the water quality goal (e.g., the waterbody is suitable for fishing or swimming). The criterion is an easily measurable water quality variable and a criterion level, or threshold, for that variable.

One of the main reasons to be concerned about is that it can affect a waterbody's designated uses. As a result, states and tribes have set water quality criteria for a range of pollutants or sources of pollution to safeguard the designated uses. However, in cases where there are no obvious criterion variables with clear thresholds for a particular pollutant or pollution sources of concern, the process of setting criteria is much more difficult.

Many states and tribes are currently struggling with how to set criteria for one of the most troublesome water quality problems. According to the United States

Environmental Protection Agency (USEPA), (Environmental Protection Agency 2002) the number one water pollution problem for U.S. lakes, reservoirs, and ponds is eutrophication. Excessive nutrients, such as nitrogen and phosphorus, lead to eutrophication, a condition that can include low oxygen levels, noxious algal blooms, and fish kills (Novotny and Olem 1994, Chapra 1997).

Eutrophication is caused by excessive nutrients, such as nitrogen and phosphorus. USEPA encourages states to adopt nutrient criteria, by which they mean any measurable water quality variable or variables that can be used to detect eutrophication and measure the extent of the impairment (e.g. clarity, odor, algae). As a result, many states are struggling to determine what variable and criterion level they should choose.

It is each state or tribe's responsibility to develop a method for choosing nutrient criteria. The USEPA has offered guidance, called the Ecoregion Reference Waterbody Approach (Environmental Protection Agency 2000e); using this method, a state or tribe would choose one or more criterion variables and set thresholds at a percentile of the seasonal frequency distributions for those variables (Environmental Protection Agency 2000e). Other methods have been used by states (Walker et al. 2007), but the Ecoregion Reference Waterbody Approach, or some derivative thereof, appears to be the most popular method to set nutrient criteria.

The USEPA approach is a first attempt at setting nutrient criteria, but it has two major flaws. First, there is no explicit link between candidate criterion variables and a

waterbody's designated use. Thus, one cannot be assured that the variable that is chosen is a reasonable surrogate for designated use. Second, the method to set the threshold is statistically-derived from historical data; as such, it is difficult to assess whether a specific nutrient criterion is appropriate, overprotective, or underprotective (Environmental Protection Agency 2000e).

To address these flaws, Reckhow et al. (2005) proposed an alternative approach to set nutrient criteria called the predictive nutrient criteria method. Their method uses a combination of water quality data, expert elicitation, and structural equation modeling to determine the variable that is most predictive of designated use attainment (Reckhow et al. 2005). This process explicitly considers the attainment of the water quality goal and presents a procedure to quantify the appropriateness of candidate nutrient criteria. This approach was expanded upon in two subsequent papers (Kenney et al. in preparation, Kenney et al. in review) to include multiple experts, regions of lakes, and additional methods to statistically link the water quality variables to the designated use to determine which variable or variables are most predictive of the designated use. For nutrient criteria development, one of the key findings from Kenney et al. (in preparation) was that, if one could accurately model eutrophication impairment, the variable or variables that are most predictive of eutrophication are also the most predictive of the designated use.

One of the chief criticisms of the predictive nutrient criteria method (Reckhow et al. 2005, Kenney 2007, Kenney et al. in preparation, Kenney et al. in review) is that it fails

to suggest a specific criterion level for the predictive water quality variable. Doing so requires explicit consideration of a decision-maker's value trade-off between water quality and mitigation costs.

The objective of this paper is to present a decision-analytic approach to setting nutrient criteria. Specifically, we address the question: How should states and tribes choose eutrophication-related water quality criteria for their lakes and reservoirs, given the goals of minimizing cost and attaining the designated uses? To address this question, we used a combination of water quality modeling and multiattribute value analysis to determine the criterion variables and thresholds that maximize decision-makers' overall value. We applied the method to lakes and reservoirs in North Carolina, but the method could in principle be applied to any type of waterbody in any region of the United States.

### **5.3. Methods**

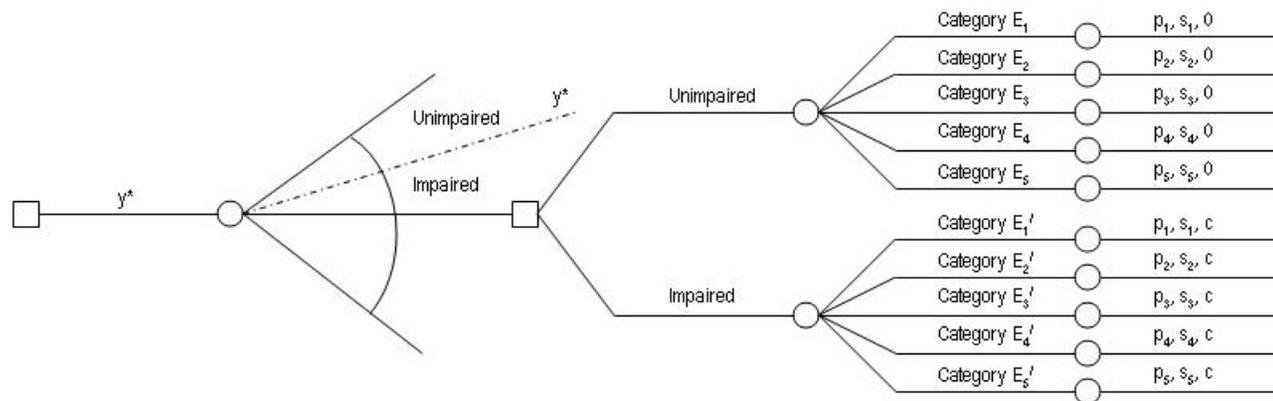
#### **5.3.1 Overview of Conceptual Model**

The decision tree (Figure 12) shows the structure of our conceptual model to choosing nutrient criteria. Our approach includes two submodels, a water quality model and a multiattribute value model.

As Figure 12 indicates, for a given criterion variable,  $Y$ , we first choose a criterion level,  $y^*$ . The second step is a chance node: a lake is selected at random. The lake's characteristics will follow a distribution based on data from real lakes in the study area.

In particular, the selected lake will have a randomly selected value  $y$  for the criterion variable. Given the value of  $y$ , the third step is a decision node which classifies the lake as unimpaired or impaired. If  $y \leq y^*$  it would be classified as unimpaired; if  $y > y^*$  it would be classified as impaired.

Decision Tree to Assist in Choosing a Criterion Level that Maximizes the Expected Value



Criterion Level	Probability Distribution for Y	Classify Waterbody as Unimpaired or Impaired	Predict Eutrophication Status	Consequences
Given a criterion variable Y, choose a candidate criterion level, $y^*$ .	If $y^*$ is the R <sup>th</sup> percentile of the distribution for Y and impairment is indicated by $Y > y^*$ , then (1-R)100% are classified as impaired	Unimpaired if $y_i \leq y^*$ Impaired if $y_i > y^*$	Conditional distribution for the eutrophication category, $E_i$ , given the waterbody characteristics.	Calculate the expected value for each $E_i$ given the attributes of primary contact recreation desirability, $p_i$ , secondary contact recreation desirability, $s_i$ , and cost, $c$ .

Figure 12: Decision Tree to Assist in Choosing a Criterion Level that Maximizes the Expected Value.

This model describes the process where, given a water quality variable, a decision maker would evaluate different nutrient criteria levels.

The fourth step is to predict the eutrophication status using a water quality model. Depending on whether the lake was classified as unimpaired or impaired, the eutrophication status (see Table 14 for definitions of the five categories) is calculated differently. If on one hand the lake is classified as unimpaired, then one assumes that there are no mitigation actions implemented and a predictive model is used to assess the eutrophication status based on the current characteristics of the lake. If on the other hand the lake is classified as impaired, then one assumes that mitigation actions are taken to improve the lake. As a result, for the impaired lake one needs to calculate the eutrophication status after improvement. Therefore, a model is used to assess the improvement in the water quality variables and then the improved water quality variables are used to parameterize a model to assess the predicted eutrophication status after improvements are implemented.

The fifth and final step is to calculate the value of a criterion level choice using a multiattribute utility model. The values for the designated use attributes are linked to the eutrophication status predictions; the costs are only incurred if the lake is classified as impaired and mitigation actions are required.

**Table 14: Eutrophication Categories used in the Expert Elicitation Assessment of Eutrophication**

Category	Description
1	The lakes have: excellent water clarity, no color, very little algae, very low nutrient levels, very high oxygen, no odor, and very healthy, abundant aquatic life.
2	The lakes have: good water clarity, little color, little algae, low nutrient levels, high oxygen, little odor, and healthy, abundant aquatic life.
3	The lakes have: fair water clarity, some color, moderate amounts of algae, moderate nutrient levels, moderate oxygen, little odor, and somewhat healthy, abundant aquatic life.
4	The lakes have: poor water clarity, noticeable color, high algae, high nutrient levels, low oxygen, noticeable odor, and unhealthy, scarce aquatic life.
5	The lakes have: poor water clarity, considerable color, very high algae (likely scums), very high nutrient levels, low to no oxygen, strong offensive odor, and unhealthy, scarce aquatic life or no aquatic life.

The categories were also used during the utility assessment (see Figures 13 and 14). These categories were designed to span the range of trophic status symptoms.

### **5.3.2 Water Quality Model**

The ultimate goal of our model is to choose an optima criterion level  $y^*$ . As described above, the water quality model allows us to generate simulated waterbodies that are representative of actual waterbodies in the study region.

#### ***5.3.2.1 Site Description and Water Quality Dataset***

This study focused on lake and reservoirs in North Carolina, including 132 lakes and reservoirs from the Blue Ridge to the Piedmont to the Coastal Plain. (See Appendix E for descriptive statistics for each of the North Carolina lakes and reservoirs.) The data were obtained from the North Carolina Department of Natural Resources (NCDNR), Division of Water Quality (NCDWQ) and include chemical, physical, and biological water quality variables from 1981 – 2004. We focused on seven state-measured eutrophication-related water quality variables. Descriptive statistics are show in Table 15, with Spearman rank correlations in Table 16.

**Table 15: Eutrophication-related Water Quality Data for the State of North Carolina**

<i>Water Quality Variable</i>	<i>Sample size</i>	<i>Descriptive Statistics and Input Values</i>	<i>Distribution</i>	<i>Sources</i>
<b>Nutrients</b>				
Total Nitrogen	n = 3707	$\mu = 0.583$ ; $\sigma = 0.478$ ; correlated Table 16	Log-normal	NCDWQ dataset
Total Inorganic Nitrogen	n = 3708	$\mu = 0.164$ ; $\sigma = 0.336$ ; correlated Table 16	Log-normal	NCDWQ dataset
Total Phosphorus	n = 3713	$\mu = 0.0552$ ; $\sigma = 0.0632$ ; correlated Table 16	Log-normal	NCDWQ dataset
<b>Algal Growth</b>				
Chlorophyll a	n = 3522	$\mu = 24.0$ ; $\sigma = 50.7$ ; correlated Table 16	Log-normal	NCDWQ dataset
<b>Oxygen</b>				
Dissolved Oxygen	n = 3689	$\mu = 8.41$ ; $\sigma = 2.19$ ; correlated Table 16	Log-normal	NCDWQ dataset
<b>Water Clarity</b>				
Secchi Depth	n = 3714	$\mu = 1.34$ ; $\sigma = 1.17$ ; correlated Table 16	Log-normal	NCDWQ dataset
Turbidity	n = 3264	$\mu = 6.04$ ; $\sigma = 6.79$ ; correlated Table 16	Log-normal	NCDWQ dataset

**Table 16: Spearman Rank Correlations for North Carolina Water Quality Dataset**

	Total Nitrogen	Total Inorganic Nitrogen	Total Phosphorus	Chlorophyll a	Dissolved Oxygen	Secchi Depth	Turbidity
Total Nitrogen	1						
Total Inorganic Nitrogen	0.307	1					
Total Phosphorus	0.317	0.136	1				
Chlorophyll a	0.341	0.0451	0.361	1			
Dissolved Oxygen	0.146	0.0276	0.146	0.137	1		
Secchi Depth	-0.296	-0.150	-0.355	-0.337	-0.120	1	
Turbidity	0.439	0.199	0.454	0.408	0.236	-0.390	1

All correlations were significant at  $p < 0.001$

### **5.3.2.2 Expert Elicitation Data**

Ideally, we would like to assess designated use attainment. Since we cannot directly measure the designated use, we must determine which measured variables are effective indicators of eutrophication-related designated use impairments. We established in Chapter 4 if one can determine which variables are most predictive of eutrophication, then those variables would also be the most predictive of designated use impairments.

Since eutrophication is a condition, there is not a single measured variable that is a perfect indicator of the eutrophication status of a waterbody; instead several water quality variables are useful indicators of different aspects of eutrophication conditions. Using a constructed scale of eutrophication status, we can provide descriptions, from very low levels to very high levels, of the eutrophication conditions (Table 14). Because we cannot directly assess the eutrophication category, we can use experts to translate between the measured water quality variables and the eutrophication status. This translation occurred using an expert elicitation process.

Expert elicitation is a formal method to quantify judgments from experts (Morgan and Henrion 1990, Keeney and Von Winterfeldt 1991, Meyer and Booker 1991). We developed an assessment that contained four steps: (1) selection and preparation of experts with knowledge of lake and reservoir eutrophication in North Carolina; (2)

individual discussion with each expert of eutrophication conditions and designated use attainment; (3) individual expert elicitations using the five constructed eutrophication categories (Table 14); and (4) a post-interview follow-up with each expert to calibrate the individual assessments and to confirm or adjust the expert's judgment.

Part 3 of the elicitation deserves elaboration. In part 3, we provided the experts with a row of correlated water quality data and asked him/her to provide a probability distribution of eutrophication status. As a result, the eutrophication status is a conditional probability distribution given the water quality data. Using these conditional distributions and the associated water quality data, we can parameterize statistical water quality models to predict the eutrophication status category of a waterbody. The expert elicitation procedure and the predictive model are described in detail in Chapter 4.

### ***5.3.2.3 Trophic State Improvement Models***

One determines whether a waterbody is impaired or not by comparing values of  $y$  to  $y^*$ , the criterion level. If the value is acceptable, or meets the criterion, then the waterbody is classified as unimpaired. In this case, we can assume status quo and use the current water quality values to predict the eutrophication status.

If, on the other hand, the waterbody does not meet the criterion, it is classified as impaired, and a process is undertaken to research and then implement mitigation

actions to improve the eutrophication status. This process is started with the waterbody being placed on the 303(d) list of impaired waterbodies; this step initiates a total maximum daily load (TMDL) assessment. A TMDL is a calculation of the maximum amount of pollutant a waterbody can receive and still meet the water quality standard. This calculation is made using a model and then, given the results of the model, the state assigns point and nonpoint source pollution reductions. These reductions are then implemented, which involves costs. If the waterbody is classified as impaired, we are interested in predicting the improvement in the water quality variables, and using these values to predict the eutrophication status, given improvements. We were particularly interested in predicting improvement of four water quality, or trophic state, variables: total phosphorus, total nitrogen, Secchi depth, and chlorophyll a. To calculate the improvement in these variables, we used two established models: Eutromod (Reckhow 1988b) and a chlorophyll – nutrient regression model (Reckhow 1993).

Eutromod provides a nutrient model for multiple regions in the U.S.; we used the Eutromod model for the Southeastern region. In Eutromod, the two nutrient equations for phosphorus and nitrogen are essentially specification of a general mass balance equation, which was based on simple mechanistic descriptions of conservation of mass,

$$\eta = \frac{\eta_f}{1 + g t} \quad (9)$$

where

$\eta$  = in-lake nutrient concentration (mg/L),

$\eta_f$  = influent nutrient concentration (mg/L),

$t$  = hydraulic detention time or residence time (yr), and

$g$  = nutrient trapping parameter (1/yr).

The model was specifically applied to calculate the improvement in total phosphorus and total nitrogen. For total phosphorus, the model was empirically fit using data obtained from the USEPA's National Eutrophication Survey. The phosphorus model is

$$\log_{10} TP = \log_{10} \left( \frac{TP_f}{1 + g t} \right) \quad (10)$$

where

$$g_{TP} = 3.0 (TP_f)^{0.53} (t)^{-0.75} (d)^{0.58} \quad (11)$$

and

TP = in-lake total phosphorus concentration (mg/L),

TP<sub>f</sub> = influent total phosphorus concentration (mg/L),

t = hydraulic detention time or residence time (yr),

g<sub>TP</sub> = nutrient trapping parameter for total phosphorus (1/yr), and

d = mean depth (m).

In our application, we used the in-lake total phosphorus concentration (TP) to be equivalent to the improved total phosphorus concentration (TP<sub>imp</sub>). The TP<sub>f</sub> values were drawn from Y, the unimproved distribution of total phosphorus (Table 1). The values for t and d were drawn from a log-normal distribution using values from the USEPA National Eutrophication Survey dataset (Reckhow 1988b). These values for t were: mean = 0.39 yr, median = 0.18 yr, minimum = 0.015 yr, and maximum = 41 yr; for d these values were: mean = 12 m, median = 10 m, minimum = 1.5 m, and maximum = 3.2 m.

For total nitrogen, the model is similar to the total phosphorus model. The total nitrogen model is

$$\log_{10} TN = \log_{10} \left( \frac{TN_f}{1 + g t} \right), \quad (12)$$

where

$$g = 0.67(t)^{-0.75} \quad (13)$$

and TN is the in-lake total nitrogen concentration (mg/L),  $TN_i$  is the influent total nitrogen concentration (mg/L), and  $g_{TN}$  is the nutrient trapping parameter for total nitrogen (1/yr). The other variables are as previously identified. Similar to total phosphorus, in our application, we used the in-lake total nitrogen concentration (TN) to be equivalent to the improved total nitrogen concentration ( $TN_{imp}$ ). For our study, the  $TN_i$  values were drawn from the unimproved distribution of total nitrogen (Table 1).

Using the prediction of the two causal nutrient variables, total phosphorus and total nitrogen, we can use these values in regression models to predict the improvement of two response variables, Secchi depth and chlorophyll a. The Secchi depth model was from Eutromod (Reckhow 1988b) and the chlorophyll a model was from a chlorophyll – nutrient regression model (Reckhow 1993).

The model for the median summer Secchi depth model is

$$\log_{10}(SD) = -0.470 - 0.364 \log_{10}(TP_{imp}) + 0.102 \log_{10}(t) + 0.137 \log_{10}(d), \quad (14)$$

and SD is the Secchi depth (m). This model does not include TN since the addition of this variable did not improve the model fit.

Chlorophyll a regression model was estimated using data from lakes and reservoirs in North Carolina. The chlorophyll a model is

$$\log_{10}(Chla) = 2.330 + 0.775 \log_{10}(TP_{imp}) + 0.317 \log_{10}(TN_{imp}), \quad (15)$$

and Chla is chlorophyll a ( $\mu\text{g/L}$ ). Because equation 15 was developed specifically for North Carolina lakes and reservoirs, it provides a reasonably accurate representation of the chlorophyll a concentrations as a result of a reduction in nutrient inputs.

There were no models to predict improvement for total inorganic nitrogen, dissolved oxygen, and turbidity. Therefore, for these three variables we assumed that the distribution for the improved condition was exactly the same as the values for the unimproved condition.

#### **5.3.2.4 Binomial Regression Model (BRM)**

After determining whether the waterbody is classified as impaired or not and then predicting, for the impaired lakes, the change in the trophic state variables after pollution mitigation actions are taken, it was necessary to develop a model to randomly generate the eutrophication status given either the unimpaired water quality data profile or the impaired water quality data profile.

To aid in this assessment, we created the binomial regression model (BRM). The BRM, unlike other similar models (see Chapter 3 and 4), predicts the probability of being in a particular eutrophication category, or the average distribution over the eutrophication categories (for example, values provided as category 1 = 0, category 2 = 0.2, category 3 = 0.5, category 4 = 0.3, and category 5 = 0), instead of a single value average of the eutrophication category (for example, average category = 2.5).

Using the results from Chapter 4, we made two assumptions with this model. First, we chose to develop a statewide model to predict the eutrophication category, since we assumed that there were nonsignificant ecoregional differences. Second, we assumed that if we could determine which variables were most predictive of eutrophication, these variables would also be the most predictive of the designated uses; therefore, the model predicts the eutrophication status, not the designated use status.

The model was parameterized with two types of data: water quality data (either for the unimpaired condition or the impaired condition) and expert elicitation data. We used untransformed water quality data, since the untransformed data best fit our model and its assumptions. Also, we used the expert judgments provided during the elicitation to quantify the eutrophication status; these judgments were provided as a distribution over the five categories for each of the rows of water quality data.

To minimize expert-specific bias in the assessment of the distributions across eutrophication categories, we first averaged the eutrophication distributions among all experts, i.e.

$$\pi_i = \frac{\sum_{k=0}^m \pi_{ik}}{m}, \quad (16)$$

where  $\pi_{ik}$  is expert  $k$ 's assessment of the probability of the eutrophication status being in category  $i$  and  $m$  is the number (14) of experts in this study. This equation provides us with the average distribution over the eutrophication categories.

Using the average distributions over eutrophication categories (equation 16), we then extracted the mean probability for each such distribution by calculating the expected value of the distribution and dividing by the number of eutrophication categories

$$p' = \frac{\sum_{i=0}^n i * \pi_i}{n}, \quad (17)$$

where  $p'$  is the mean probability,  $i$  is the eutrophication category,  $\pi$  is the average distribution over eutrophication categories, and  $n$  is the total number of eutrophication categories (i.e.,  $i = 0, 1, 2, 3, 4$ , for a total of 5 eutrophication categories; for the binomial distribution,  $n = 4$ ).

A useful property of the binomial distribution is that it is fully characterized by the variables  $p'$  and  $n$ . Since  $n$  is fixed at 4, each expert distribution over eutrophication categories,  $\pi$ , can be characterized and reconstructed from the predicted values of  $p'$  alone. In other words, for a given value of  $p'$ , the probability in eutrophication category,  $i$ , is determined from

$$P(X = i) = \frac{n!}{i!(n-i)!} p'^i (1-p')^{n-i} . \quad (18)$$

Using equation 18, we can estimate the conditional probabilities for each eutrophication category.

Taking advantage of the preceding facts, we regress the predicted  $p'$  against all the water quality variables

$$p' = \alpha + XB , \quad (19)$$

where  $X$  is the matrix of water quality variables and  $B$  is the vector of regression coefficients. Combining the binomial model with regression allowed us to generate a distribution of eutrophication categories from a given profile of water quality characteristics.

The final BRM equation for  $p'$ , with unstandardized coefficients, is

$$p' = 0.079TN + 0.046TIN + 1.4TP + 0.0073Chla + 0.025DO - 0.037Secchi + 0.0030Turb . \quad (20)$$

Thus given a profile of water quality data, we can predict the mean probability,  $p'$ , and then use this value in a binomial distribution to calculate the eutrophication category (equation 18). Applying the procedure many times, we can develop a distribution over the eutrophication categories.

Using this water quality model, we now have a procedure to generate conditional binomial distributions for waters that are classified as unimpaired, hence unimproved, as well as waterbodies that are classified as impaired, hence improved. As a result, we can translate the water quality data into a prediction of the eutrophication category. This information is one of the key inputs to the multiattribute value model.

### 5.3.3 Multiattribute Value Model

To assess the achievement of the three objectives, primary contact recreation desirability, secondary contact recreation desirability, and cost, we constructed an additive multiattribute objective function (Keeney and Raiffa 1976, Keeney 1992)

$$V(E_h) = w_r v_r(r(E_h)) + w_s v_s(s(E_h)) + w_c v_c(c(y_h)) \quad , \quad (21)$$

where

$w_r, w_s, w_c$  = weights for the attributes of primary contact recreation (r), secondary contact recreation (s) and, cost (c),

$v_r, v_s, v_c$  = values for the respective levels of the attributes of primary contact recreation (r), secondary contact recreation (s) and, cost (c),

$E_h$  = eutrophication status for waterbody h,

$y_h$  = measured level of nutrient criterion for waterbody h,

$r(E_h)$  = level of primary contact recreation value as a function of  $E_h$ ,

$s(E_h)$  = level of secondary contact recreation value as a function of  $E_h$ , and

$c(y_h)$  = cost associated with waterbody h if it is classified as impaired given the value of  $y_h$ .

### **5.3.3.1 Value / Utility Assessment**

Setting environmental criteria requires policy makers to consider multiple objectives and trade-offs, making this decision quite complicated. Though other methods of environmental standard setting have provided various means of selecting the variable and level (Chapters 3 and 4), none of the methods have directly addressed competing designated uses and trade-offs between maximizing environmental protection and minimizing cost. Fortunately, there is a method to assist in making decisions with multiple objectives.

The goal of a value or utility assessment is to formally quantify preferences among multiple objectives (Keeney 1977). Using the decision-makers' preferences we can calculate the optimal decision(s) with a preference model, such as a multiattribute value model. As a result, we can assist the decision-makers in evaluating different policy choices so that they can make decisions that they believe will best maximize their objectives.

In this study we considered three attributes: two designated uses, primary contact recreation and secondary contact recreation, and cost. We talked with K.H. Reckhow to determine whether or not the attributes were independent, or whether he believed a change in one attribute would affect the preference of another attribute. He stated that, within the range of water quality of North Carolina lakes and reservoirs, he believed that the desirability of a waterbody for swimming is independent of the

desirability of a waterbody for fishing and both were independent of cost. As a result, we assumed additive independence and specified an additive value function:  $V = \sum w_a v(l)_a$ , where  $k_a$  is the weight for attribute  $a$  and  $v(x)$  is the value of an attribute level  $l$  for attribute  $a$ .

Since standard setting is informed by scientists, but standards are not set by scientists, it was essential to assess the weight and value judgments from the individuals who would make the decisions. The assessment process consisted of five steps, which support the best practices presented in Keeney (1977): (1) selection of decision-makers and preparation for the assessment tasks, (2) assessment of the individual value functions, (3) assessment of the trade-offs between the attributes, (4) consistency checks and modifications to the value function and trade-offs, and (5) aggregation of multiple decision-makers' preferences. Since we had little time with each person, we could not directly assess attribute independence, but assumed that the decision-makers would support K.H. Reckhow's statements about attribute independence. (See Appendix D for full value assessment reports for each NCEMC decision-makers included in this study.)

### **5.3.3.2 Step 1: Selection and Preparation of Decision-Makers**

To assess the appropriate preferences for our model, it was essential to assess the preferences from individuals who make environmental policy decisions in North

Carolina. Therefore, we assessed the value judgments of four members from the North Carolina Environmental Management Commission (NCEMC). These decision-makers were identified by K.H. Reckhow to be knowledgeable in North Carolina water policies and thoughtful in complex decision-making involving difficult trade-offs. After the decision-makers agreed to participate in the study, they were informed of the motivation for this assessment and the specific assessment tasks. To ensure that the decision-makers understood these tasks, we answered any questions about the assessment procedure.

#### **5.3.3.3 Step 2: Assessment of the Value Function of each Attributes**

We assessed the value functions for each of the attributes: primary contact recreation desirability, secondary contact recreation desirability, and cost. The attribute cost was assessed using the natural scale of money in United States dollars (USD). If it was classified as unimpaired, the cost was set to \$0; if it was classified as impaired, annual assessment and implementation costs of a mitigation plan could range from 1 million USD to 5 million USD.

For primary contact recreation and secondary contact recreation, we employed an unusual method to assess the value function. Instead of assessing the value on a scale that was directly related to these attributes, we assessed the value of primary and secondary contact recreation for each of the categories of eutrophication status (Table

14). For the modeling we needed the value of these two attributes in relation to the eutrophication categories. Since our decision-makers were familiar with eutrophication and water quality issues in North Carolina, as well as being in the NCEMC, they were able to easily translate the value of primary or secondary contact recreation for each eutrophication category (This assumption was extensively tested pre-value assessment). Therefore, for the designated use attributes, we have the value of the attribute for each of the five categories of eutrophication status (for example of set-up see Figures 2 and 3).

All value functions were assessed using the best practices protocol and modified to suit our particular needs by consulting literature utility and value assessment protocols (Keeney 1977, Meyer and Booker 1991). We assessed the value functions for each individual decision-maker by asking him or her questions so that we could develop the general shape of the value function. An example of one such question is, "For the eutrophication category 3, is the value for primary contact recreation closer to the optimal value, 1, the worst value, 0, or exactly in between?" Continuing to ask questions that narrowed allowed us to determine the exact values for the different categories.

Quantifying preferences is not easy; however, when conducting the assessment we adapted to the situation and person. Thus, we modified the wording or rephrased questions so that it would be easy for a decision-maker to respond. Doing so is more of an art than an exact science (Keeney 1977), but we were able to confirm that their

responses reflected their preferences by asking additional clarifying questions and checking for consistency in their responses.

For the attribute of cost, all of the decision-makers independently stated that their value function for cost is linear; similarly, the group and average cost value functions were also linear. The decision-makers also confirmed that their value function was equivalent to their utility function. The value functions for primary contact recreation and secondary contact recreation were more complex.

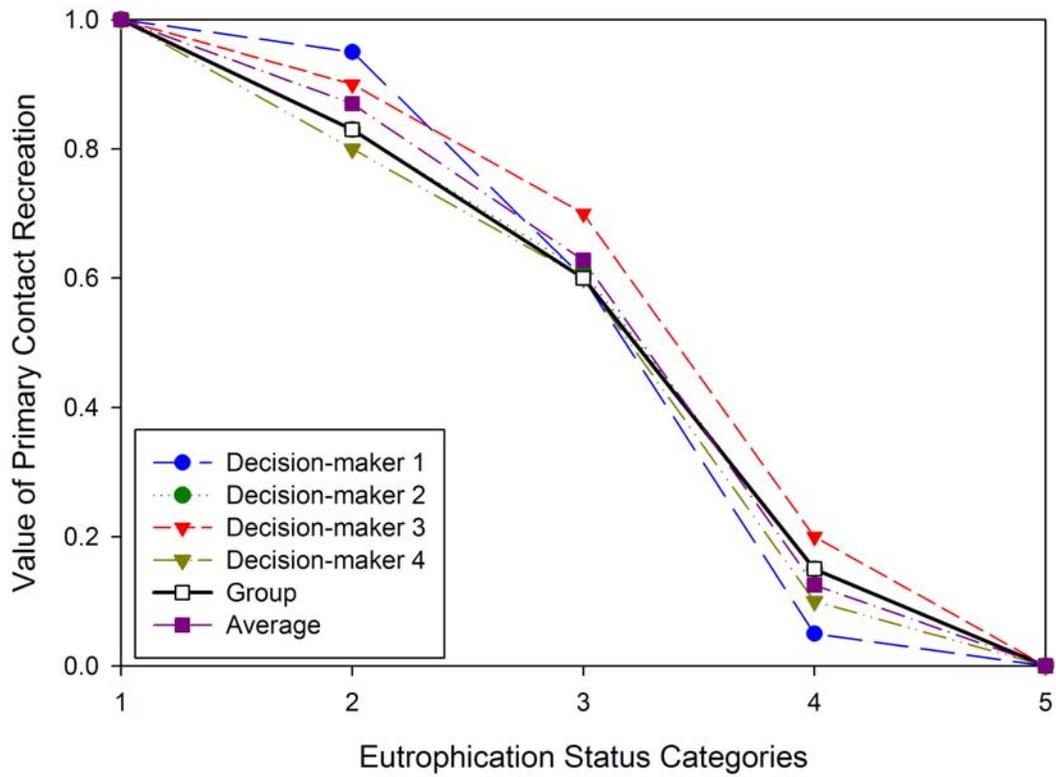
For primary contact recreation, all the decision-makers thought that the value function was S-shaped where best trophic status category was a 1 and the worst trophic status category was a 5 (Figure 13). Their decision-makers' values are remarkably similar for each of the eutrophication status categories, differing by at most 15%.

Stepping through the process to create the primary contact recreation value function, during the individual assessments, all the decision-makers independently agreed that, for primary contact recreation, a eutrophication status category 3 was closer in value to the ideal eutrophication category (1) than the worst eutrophication category (5). Additionally, the decision-makers also thought that a category 2 was closer to a category 1 than a category 3, and they stated that a category 4 was closer in value to a category 5 than a category 3. The decision-makers independently confirmed their values by explaining that they thought there was a greater loss in value for primary contact recreation below a category 3.

Interestingly, the group assessment values and the equal-weighted average values were virtually the same. Since the group assessment involved compromise, in that the decision-makers had to choose a value that they all agreed upon, it is not surprising that there was little difference between these two methods of combination, given that the individual assessments were fairly similar.

The secondary contact recreation value function was similar to that for primary contact recreation in that all the decision-makers thought that the value function was S-shaped where the best eutrophication category was a 1 and the worst eutrophication category was a 5 (Figure 14). There was notable agreement between decision-makers for each of the categories; the largest difference in values (25%) was assigned to category 4. In comparison to the primary contact recreation value function, secondary contact recreation retains more of its value for the eutrophication status categories 2, 3, and 4. Finally, for reasons similar to those discussed previously, there was little difference in the group assessment values and the mean values.

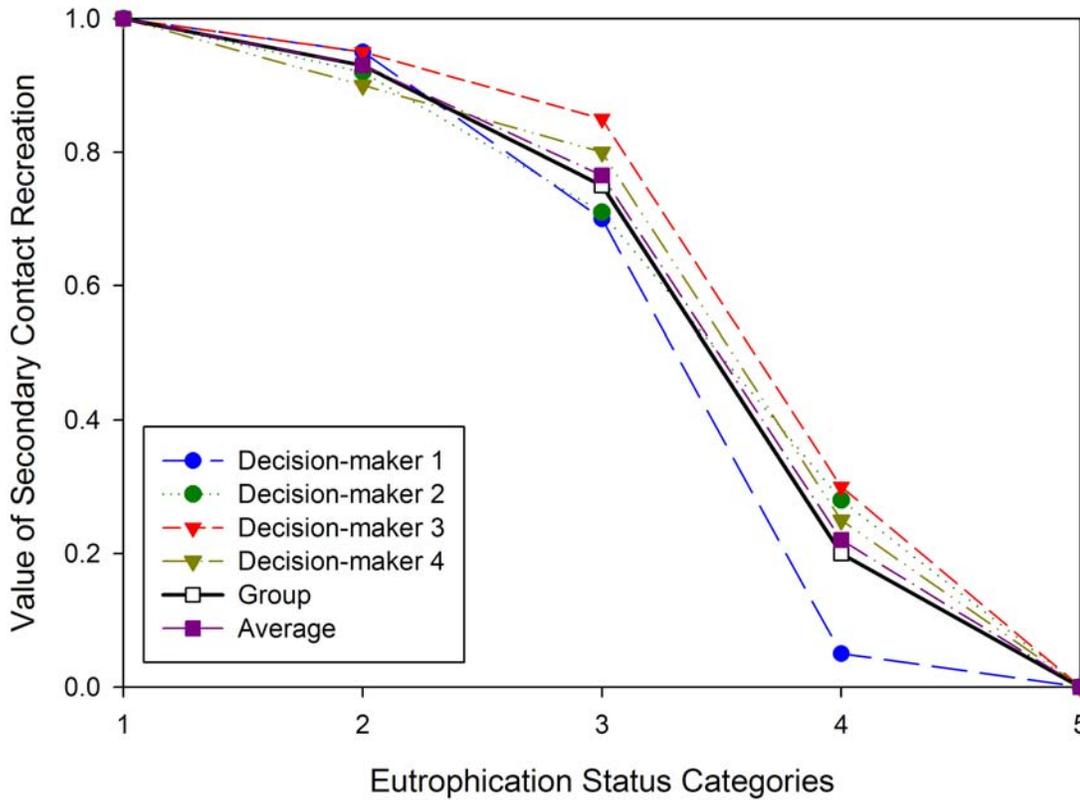
### Value Function for Primary Contact Recreation for the Range of Eutrophication Status Using All Decision-Makers



**Figure 13: Value Function for Primary Contact Recreation for the Range of Eutrophication Status using all Decision-makers**

All decision-makers agreed that it was a decreasing function and their values were no greater than a difference of 15%. We assumed a linear extrapolation between the five points that were directly assessed

### Value Function for Secondary Contact Recreation for the Range of Eutrophication Status Using All Decision-Makers



**Figure 14: Value Function for Secondary Contact Recreation for the Range of Eutrophication Status using all Decision-makers**

All decision-makers agreed that it was a decreasing function and their values were no greater than a difference of 25%; eutrophication category 4 had the most uncertainty. We assumed a linear extrapolation between the five points that were directly assessed.

#### **5.6.3.4 Step 4: Assessment of Trade-offs between Attributes**

After we assessed the value functions for primary contact recreation desirability, secondary contact recreation desirability and cost, we assessed the weights,  $k_i$ , for each attribute using a pricing-out approach. With this approach, each decision-maker determined the amount he or she would be willing to spend to achieve different levels of primary or secondary contact use attainment.

We asked the decision-makers questions such as, “Would you prefer primary contact recreation at its best level with cost at its worst level, or would you prefer primary contact recreation at its worst level with annual cost at \$C?” By adjusting C in subsequent questions, we were able to find the point where a decision-maker was indifferent between a particular level of recreation and specific value for cost. The judgments allowed us to calculate the attribute weights in the additive value function.

Comparing the calculated weights (Table 18), the attribute weights were distributed in the following order, from highest to lowest: primary contact recreation, secondary contact recreation, and cost. These results support the rankings provided verbally by the decision-makers. Additionally, the attribute weight assignments were incredibly similar across the decision-makers, differing by less than 10% for each of the attributes. The difference in the weights for the group vs. the average differed by less than 2% for all three attributes.

**Table 18: Trade-off Weights between the Attributes**

	Decision-maker 1 Weights	Decision-maker 2 Weights	Decision-maker 3 Weights	Decision-maker 4 Weights	Group Weights	Average Weights
Primary Contact Recreation	0.37	0.40	0.36	0.43	0.39	0.390
Secondary Contact Recreation	0.33	0.35	0.34	0.32	0.35	0.335
Cost	0.30	0.25	0.30	0.25	0.26	0.275

These values were provided during both the individual and group assessments. The decision-maker weights represent the individual trade-off weights of each expert, the group weights that best reflect the group, and the average weights is an equal-weighted average of the four individual assessments. The rankings of the attributes using their weights were the same for each participant. Moreover, there was remarkable agreement on the weight values between participants, particularly given that weights were first assessed during separate interviews.

#### **5.6.3.5 Step 4: Consistency Checks and Modifications**

During the assessment, we asked questions to check the consistency of the decision-makers' judgments. These checks may have included asking a decision-maker to justify a choice that was difficult, providing clarifying guidance when he or she provided a preference judgment that seemed inconsistent with previous judgments or statements, and asking the same questions in different ways to see if his or her response changes. In addition to checking the decision-maker's value assessments, we tested to see if his or her value assessments were consistent with his or her utilities by asking lottery questions. The lotteries were set up to see whether or not a decision-maker thought that a certain choice with a particular value was essentially the same as an uncertain choice with the same expected value, thus testing whether there was a difference between their values and utilities. Given the decision-makers responses, their values are more or less equivalent to their utilities.

After the assessment, the decision-makers' value functions and trade-offs were summarized and the decision-makers were allowed to make any modifications they felt were necessary to better reflect their preferences. The final values were used in the additive value model for that individual.

#### **5.6.3.6 Step 5: Decision-Maker Preference Combination**

Since we used multiple decision-makers' preferences, it is important to appropriately aggregate these assessments. For this study, we aggregated preferences in two ways. First, we calculated the average additive value function. Second, we convened three of the decision-makers (the fourth was unavailable) and asked them to try to arrive at a consensus for the weights and individual value functions. Only one hour was available for this task, but by focusing on the judgments with the greatest differences, the decision-makers arrived at consensus with little controversy.

#### **5.3.4 Water Quality Models and Multiattribute Value Model**

Recalling our description of the decision tree (Figure 12), the approach includes two submodels, a water quality model and a multiattribute value model, which are connected through Monte Carlo simulations. The procedure describing how these models combine is best illustrated through an example.

Suppose we have one lake that is characterized by the following water quality profile (also described as the water quality profile given it is unimproved):

total nitrogen = 0.32 mg/L

total inorganic nitrogen = 0.06 mg/L

total phosphorus = 0.05 mg/L

chlorophyll a = 25  $\mu\text{g/L}$

dissolved oxygen = 9.4 mg/L

Secchi depth = 1.4 m

turbidity = 2.5 NTU

If the water quality criterion was 0.06 mg/L of total phosphorus, then this lake would be classified as unimpaired since the measured total phosphorus level of 0.05 mg/L is less than the criterion level of 0.06 mg/L. Then, we can predict the eutrophication category, given the water quality profile above, by using these data in BRM (equation 11). Performing this calculation and then using this estimated probability in the binomial distribution, the model indicates that the highest probability for the lake eutrophication status is on category 3. Now, we can use the results of the water quality models in the multiattribute model to estimate the expected value.

From the water quality model we need the eutrophication status category, and we have to know whether the lake was classified as unimpaired or impaired. First, given a eutrophication status category 3, we can use the value functions (Figures 13 and 14) to determine the value for the attributes primary and secondary contact recreation desirability. In this case, using the group value function, the value for these attributes is 0.6 and 0.75, respectively. Next, we can determine the value for cost based on whether it was classified as unimpaired or impaired. If the waterbody is classified as unimpaired,

as in this case, the cost is zero and the value is 1. Combining these values with the attribute weights for the group, we can calculate the expected value, which, in this example, is 0.7565.

Now let us suppose that the criterion is more stringent, 0.03 mg/L of total phosphorus. Given this criterion level and using the values from the unimproved water quality profile, the lake would now be classified as impaired. Since the lake is impaired, we would like to know the eutrophication status if mitigation actions are taken. Using the trophic status models (equations 1-6) we can calculate the change in the values of the water quality profile. The water quality profile given improvements is:

total nitrogen = 0.23 mg/L

total inorganic nitrogen = 0.06 mg/L

total phosphorus = 0.02 mg/L

chlorophyll a = 7.04  $\mu$ g/L

dissolved oxygen = 9.4 mg/L

Secchi depth = 1.65 m

turbidity = 2.5 NTU

While the total phosphorus value of 0.02 mg/L indicates that the waterbody would be cleaned up to a level greater than criterion of 0.03 mg/L of total phosphorus, the cost model is insensitive to the level of improvement.

Now, using the water quality profile given improvement, we can predict the eutrophication category by using these data in BRM (equation 11). Performing this calculation and then using this estimated probability in the binomial distribution, the model indicates that the highest probability for the lake eutrophication status would be on category 2. Using these results, we input this information into the multiattribute value model to calculate the expected value.

Similar to the method for the unimpaired lakes, we use the eutrophication category and the impairment classification to calculate the expected value. Using a eutrophication status of a category 2, we can use the value functions for primary and secondary contact recreation desirability (Figures 13 and 14) to determine the value; using the group value function, these attribute values are 0.83 and 0.93, respectively. Next, we can assess the value for cost. Since the waterbody is classified as impaired, there are costs incurred for assessment and pollution mitigation implementation. In this case, we can assume a cost of 2.5 million USD, which corresponds to a value of 0.5. Combining these values with the attribute weights for the group, we can calculate the expected value, which, for the impaired condition, is 0.7792.

This example is for a single lake for a single water quality profile. Let us suppose that instead of a single lake we are interested in setting nutrient criteria for a region of lakes. And that instead of one water quality profile, each water quality variable has an associated distribution, which is correlated, because the water quality variables are correlated. Given a criterion level, we can use Monte Carlo methods to draw from the water quality distributions, classify the waters as unimpaired or impaired, calculate the eutrophication status, and then use this information to calculate the expected value. Performing this procedure many times, we can calculate the expected value, given the inherent uncertainty in this decision.

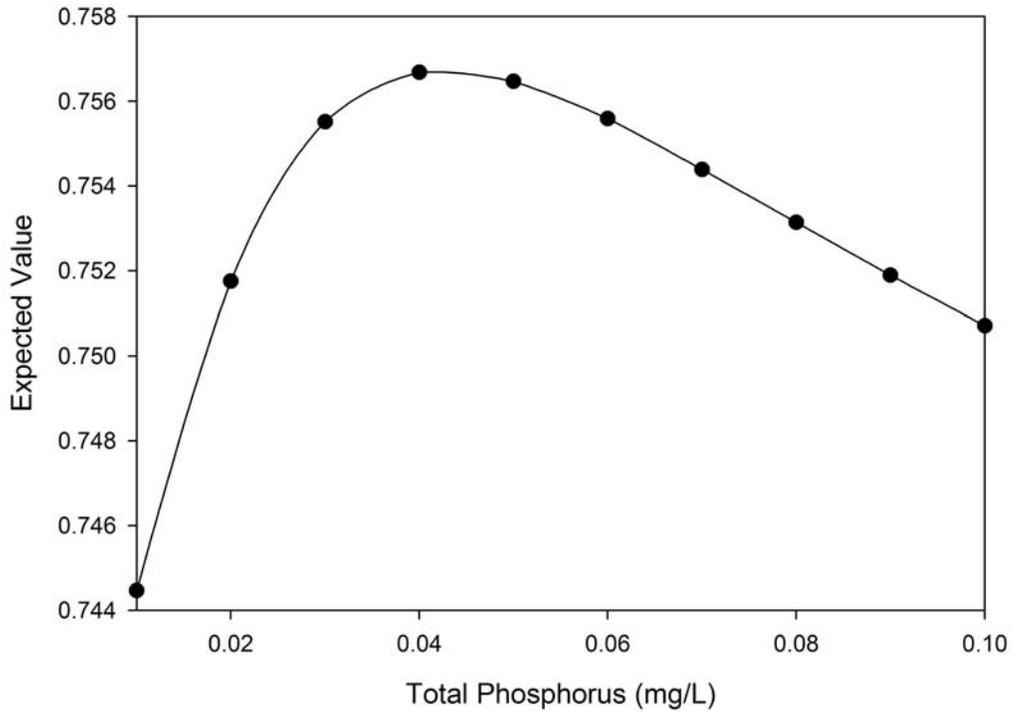
## **5.4 Results**

To determine the optimal criterion level for total phosphorus, we ran a Monte Carlo simulation for 10 equally-dispersed criterion values between 0.01 – 0.10 mg/L using 1,000,000 iterations (Figure 15). The total phosphorus criterion level that maximized the expected value was 0.04 mg/L.

The shape of the expected value curve for the total phosphorus criterion levels in Figure 15 can be better understood when considering the percentage of waterbodies classified as unimpaired vs. impaired in Figure 16. Remembering that a waterbody is classified as impaired if the total phosphorus level drawn from the distribution is greater than the criterion level, it makes sense that as the criterion level becomes less stringent

(higher levels of total phosphorus), there are more waterbodies classified as unimpaired. Incremental increases in the number of waterbodies classified as unimpaired are greatest between 0.01 mg/L to 0.03 mg/L. At the criterion level of 0.04 mg/L the number of waterbodies classified as unimpaired is 54%. The reason we care about the percentage of lakes and reservoirs classified as unimpaired vs. impaired is because it reminds us that there is an important balance between improvement and the expected cost to improve more waterbodies.

### Expected Value for the Multiattribute Value Model



**Figure 15: Expected Value for the Total Phosphorus Nutrient Criteria Multiattribute Value Model**

The model was run with 1,000,000 iterations. The optimal total phosphorus criterion level is 0.04 mg/L.

We compared the sensitivity of the maximum expected value using all of the decision-makers, the group, and the average assessments (Figure 17). As one would anticipate, the different preferences expressed by the different decision-makers affected the model results; however, the expected values differed by no more than 0.04. Additionally, the total phosphorus level that maximized the expected value was either 0.04 mg/L or 0.05 mg/L in all cases except one; for decision-maker 3 the criterion level that maximized the expected value was 0.07 mg/L. Despite these differences, there is a fairly consistent story that the optimal criterion level is not the most stringent and it is also not the most accommodating. At the same time we recognize that there is not consensus, and one could provide good arguments for using any criterion level between 0.03 mg/L and 0.07 mg/L.

The optimal total phosphorus criterion level is sensitive to the specified cost. Figure 18 shows that the optimal criterion level changes based on the costs incurred if the waterbody is classified as impaired. If there is no cost or if it is inexpensive to conduct research and implement pollution mitigation devices, then the optimal choice is to set a stringent environmental standard. If on the other hand it is costly, then the optimal criterion level would be a loose standard so that only the worst waterbodies are classified as impaired and undergo improvements.

The estimated equivalent cost of choosing a total phosphorus criterion between 0.03 mg/L and 0.07 mg/L is less than a \$100,000 annual increase in cost per lake. Relative

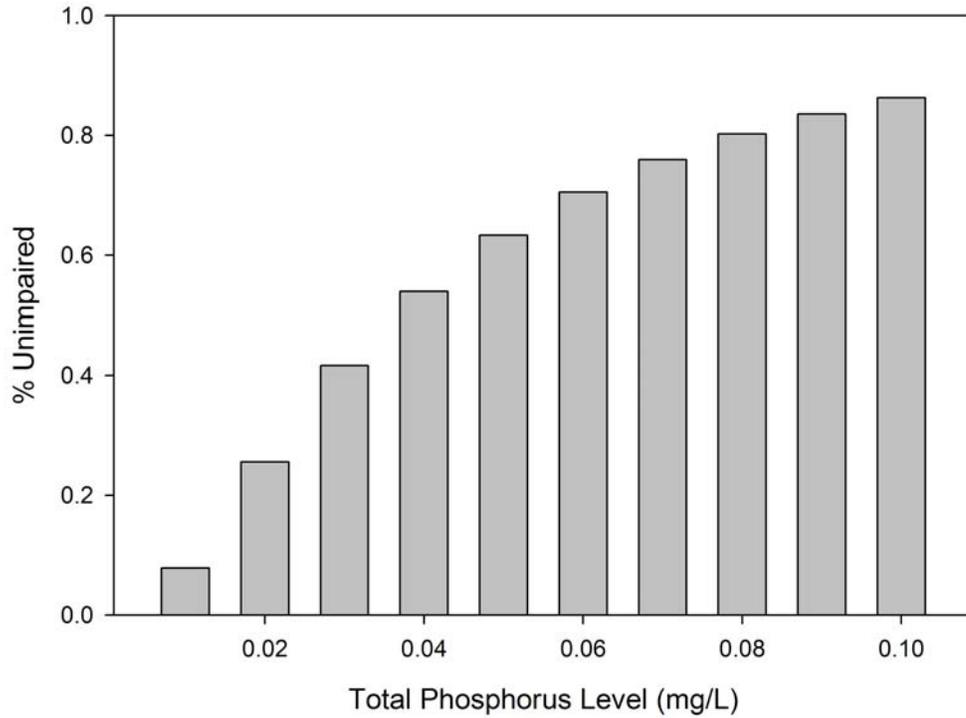
to the cost of assessment and implementation of pollution mitigation actions, if the ideal criterion level is not chosen, in the long term the choice has a small effect (approximately 4% of the mid-range of 2.5 million USD) on the cost. Therefore if the decision-makers choose a criterion level between 0.03 mg/L and 0.07 mg/L, possibly considering the number of lakes and reservoirs that would be classified as impaired, the expected allocation of resources provided by the legislation, and the number of people affected, if the cost increased by \$100,000, then the expected value would decrease by no more than 0.022.

We also tested a multiple-criteria model to evaluate whether a single nutrient criterion or multiple nutrient criteria would better determine eutrophication-related waterbody impairment. To calculate whether to use a single criterion or multiple criteria, we applied weights to each of the candidate variables.

Using weights, we can think of a situation with  $x$  candidate criteria variables. The combination of the  $x$  weights must add to 1. As a result, we can set up a scenario within the model to determine which set of weights provides us the greatest expected value. Suppose we set the threshold level equal to 1. Then we set up an optimization procedure where we are looking for the set of weights that when multiplied with the water quality variables we can compare to the threshold level. If the combination is less than or equal to 1 then the lake is classified as unimpaired; if it is greater than 1 then the

lake is impaired. Using optimization, we can search for a set of weights that would result in the highest expected value.

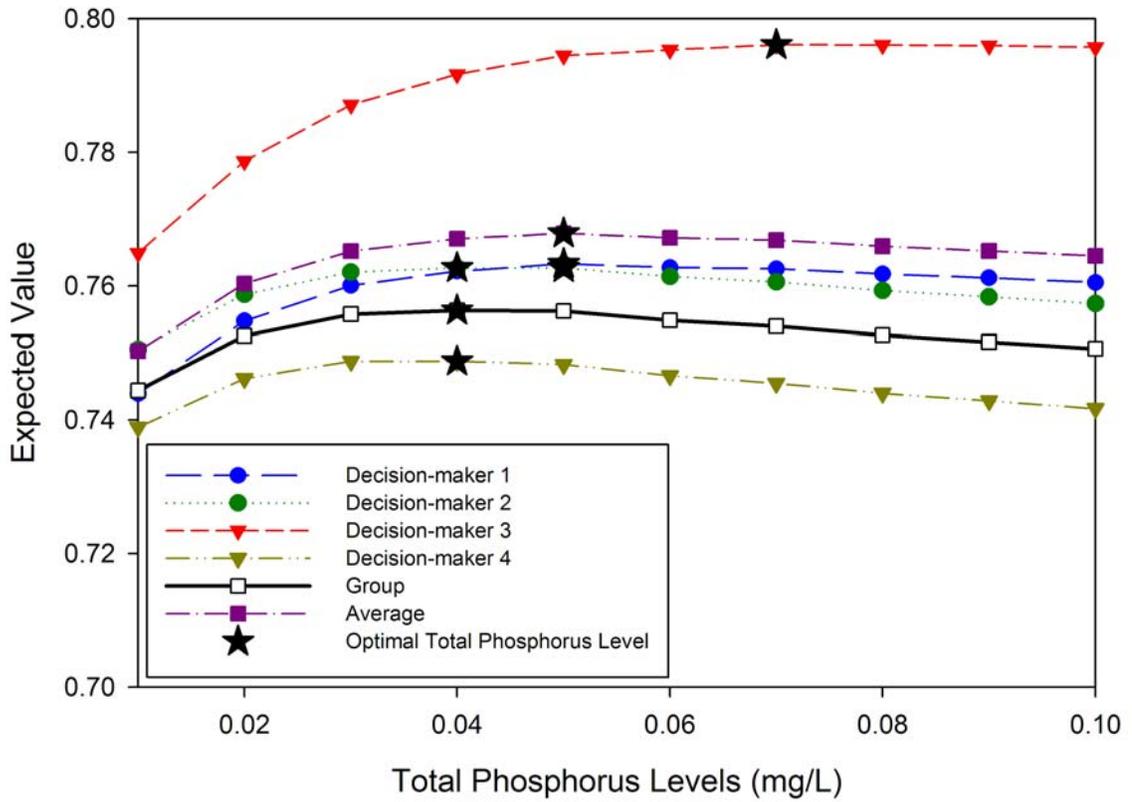
### Percentage of Waterbodies Classified as Unimpaired vs. Impaired



**Figure 16: Percentage of Waterbodies Classified as Unimpaired vs. Impaired**

As the criterion level increases, there are a higher percentage of waterbodies in compliance of the standards.

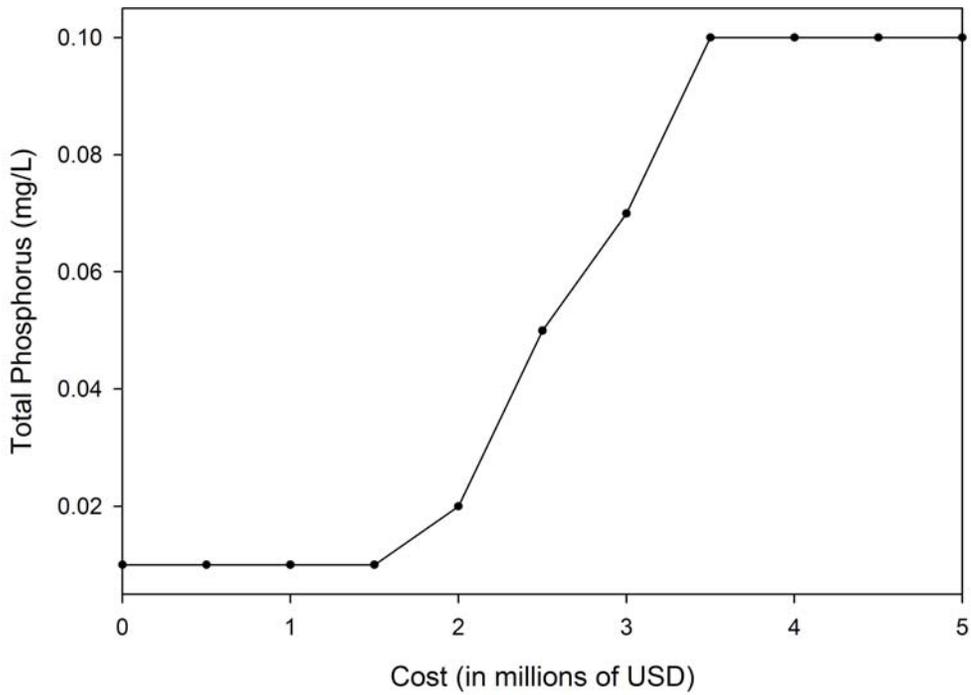
### Expected Value for a Range of Candidate Total Phosphorus Criterion Levels Using All Decision-Makers



**Figure 17: Expected Value for a Range of Candidate Total Phosphorus Criterion Levels using all Decision-makers**

There was not a single criterion level that maximized the expected value for all the decision-makers and the combined assessments. The optimal total phosphorus criterion level was either 0.04 or 0.05 for all decision-makers, the group, and the average, with the exception of decision-maker 3, whose optimal criterion level was 0.07.

### Optimal Total Phosphorus Levels for the Full Range of Costs



**Figure 18: Optimal Total Phosphorus Level for the Full Range of Costs**

The optimal total phosphorus is sensitive to the costs incurred if the waterbody is classified as impaired. If the costs are low, then the optimal criterion level is the most stringent; if costs are high, then less stringent standards are optimal.

Using this procedure, we conducted an optimization to determine the optimal weights on four candidate criterion variables: total nitrogen, total phosphorus, chlorophyll a, and Secchi depth. Of these variables, both the total nitrogen and the Secchi depth weights were near zero. Chlorophyll a was weighted at 4.9% and total phosphorus was weighed at 95%. These results indicate that there is little added benefit from using multiple variables since total phosphorus contains the majority of the weight. As a result, we confirmed that the use of a single criterion, total phosphorus, was appropriate for our application to North Carolina lakes and reservoirs.

## ***5.5 Discussion***

Choosing a criterion level is important because the criterion level is a way to indicate whether the waterbody is unimpaired or impaired using a measured water quality variable and level. If a waterbody is classified as unimpaired, then no action is taken. If however, a waterbody is classified as impaired, then action is taken which includes spending money to cleanup the waterbody. Therefore, it is important to find the criterion level that best balances the trade-off between environmental protection and cost. This assures that we are not wasting resources cleaning up waterbodies because of an overly stringent standard; conversely, we are also assured that we are appropriately targeting waterbodies for pollution mitigation before they are severely degraded.

We determined the criterion level that maximized the expected value using the preferences of the state environmental decision-making body. Based on the NCEMC decision-makers' preferences, the criterion level for total phosphorus that maximized the expected value was between 0.03 mg/L and 0.07 mg/L (Figure 15). We were unable to conclusively suggest an optimal total phosphorus level since the expected value did not change much, given the model assumptions. The optimal total phosphorus level, additionally, is sensitive to cost (Figure 18).

Because the data failed to show a difference between the ecoregions in North Carolina (Kenney et al. in preparation), this assessment was based on setting a statewide nutrient criterion instead of ecoregional criteria. This assumption is in contrast to the USEPA approach, which promotes setting criteria based on ecoregional boundaries. In North Carolina, there are three USEPA Ecoregion Level III categories (Omernik and Bailey 1997). Using these regions, the USEPA suggested total phosphorus water quality criterion levels of 0.008 mg/L for the Blue Ridge and Coastal Plains Ecoregions and 0.02 mg/L for the Piedmont Ecoregion (Environmental Protection Agency 2000a, b, 2001). Comparing the USEPA recommended levels to our results suggest that the USEPA approach for setting criteria in North Carolina is overly stringent and perhaps may not be feasible.

In addition to selecting the criterion level, we can use the model to quantitatively assess whether including one, two, or more variables would improve our ability to

predict eutrophication-related impairments of the designated use. Applying this feature of the model, the results suggested that the best criterion variable is total phosphorus. Given the mathematics of the model, it is not surprising that total phosphorus was weighted as the most predictive. The eutrophication status is calculated using the BRM, given the water quality profiles for either the unimpaired or the impaired state. If the waterbody is unimpaired, then the importance of the variable is based on how predictive the variable is in the BRM. If, on the other hand, the waterbody is impaired, then we use trophic state models to calculate the improvement in the water quality values. The response variables, Secchi depth and chlorophyll a (equations 5 and 6), are predicted given the calculated improvement in total phosphorus (equation 1) and total nitrogen (equation 3). As a result the nutrients, as causal variables, play a particularly important role in these models.

Despite the mathematics, from an ecological perspective, we were somewhat surprised that chlorophyll a was not more predictive. The fact that chlorophyll a did not perform as well as total phosphorus is likely due to the substantial sediment-related turbidity problems in North Carolina reservoirs. This type of turbidity causes significant light limitation, which means that light, and not nutrients, may be a limiting factor of algal growth (Reckhow, personal communication). Consequently, chlorophyll a may not be the best predictor of eutrophication-related problems in this region, even though it is more closely linked to eutrophication symptoms and the designated uses.

Both our results and approach differ from other methods of variable selection because we can determine the number of variables necessary to sufficiently assess impairment. In comparison to our method, the USEPA suggests using all four nutrient criteria variables, total phosphorus, total nitrogen, chlorophyll a, and Secchi depth, unless the state justifies using fewer variables. In contrast, the current North Carolina nutrient criterion was chosen by a scientific panel as 40  $\mu\text{g/L}$  of chlorophyll a. The panel chose this nutrient criterion because it is a proxy for algal growth, and thus closer to algal-related eutrophication symptoms. It is also arguably closer to the designated use, because significant algal growth is undesirable and chlorophyll a is an indicator of the algal response from nutrients. We believe that our method is an improvement over both of these methods because it provides a means to test which variable was most appropriate and whether multiple variables will improve our predictive capabilities.

In the future we would recommend improving our approach in four ways. First, many nutrient criteria have built in flexibility with the criterion level. For example, instead of setting a criterion where a waterbody is classified as impaired if a measured value exceeds the criterion level, we could explore which criterion level is optimal if X% of the samples could be exceeded. Second, we could predict improvement for total inorganic nitrogen, dissolved oxygen, and turbidity by drawing new values based on the conditional distributions of these variables given the new improvement values for total nitrogen, total phosphorus, chlorophyll a, and Secchi depth. Third, models can be

developed so that type, degree, and cost of required mitigation actions are linked to the criterion level. Finally, we could develop a Bayesian regression model to predict posterior distributions of eutrophication status.

The results of this study demonstrate that a multiattribute value or utility analysis is a useful way to help decision makers think about the decision of setting nutrient criteria. These decisions are often made in an ad hoc fashion. By explicitly considering the decision maker's trade-off weights for cost and the designated use goals, one can make a more thoughtful and transparent decision.

The current USEPA guidance for setting eutrophication-related criteria fails to address the water quality goals; an alternative method is needed. This study demonstrated one such method, using a nutrient criteria multiattribute value model, where the criterion variable and level is chosen by explicitly making trade-offs and then choosing the one that maximizes the decision maker's expected value or utility. The use of this process provides a novel and practical approach to selecting nutrient criteria.

## **6. Conclusions**

### ***6.1 Overview of Results***

This dissertation presents an approach to address the question: How should States and Tribes choose nutrient criteria to determine eutrophication-related impairments of the designated use? To address this question I used a combination of water quality modeling and decision analysis to determine the optimal nutrient criterion variables and levels.

To choose criterion variables that are predictive of the designated use, I used statistical models to link the water quality variables to eutrophication and the designated uses. The method was originally developed and tested using single waterbodies in Chapter 2. The predictive approach to nutrient criteria used structural equation modeling to assess predictive relationships among candidate water quality variables. Expert elicitation was also used to translate and quantify designated use attainment. Combining the water quality data and elicited expert judgments, we were able to identify the criterion that best predicted designated use attainment. The other key result from this chapter was the idea that the criterion levels should be set by considering the probability of compliance; a decision-maker would choose the criterion levels based on his or her risk-of-noncompliance of the designated use. This research

provided a novel approach to thinking about and setting water quality standards, which transparently differentiate between the science and value judgments.

Chapter 3 used the predictive approach to nutrient criteria framework and made two important extensions. First, the models were built for groups of lakes within the Florida Kissimmee Chain-of-Lakes. Second, the elicited probability designated use attainment was obtained using multiple experts. Using the models we determined that total phosphorus was the most predictive variable of the designated use with chlorophyll a the second most predictive variable. Using this information we were able to assess the risk of nonattainment of the designated use for these two predictive variables. This research and these results were essential to confirm the general predictive approach and to develop conclusions that were suitable for policy implementation.

In Chapter 4 we developed models to help the State of North Carolina reevaluate their nutrient criteria. These models were designed to select nutrient criteria variables for North Carolina lakes and reservoirs. This research expanded on the two previous studies by developing models for a State with multiple ecoregions; since there were multiple regions we could test whether or not there was a difference between the ecoregions. Additionally, we significantly modified the expert elicitation process so that we could assess the eutrophication category and the designated use category instead of simply probability of designated use attainment. As a result, we were able to

specifically tackle the problem of eutrophication-related impairments of the designated use, using water quality data, expert elicitation, and three statistical models (structural equation models, multiple regression, binomial multiple regression). Using and applying the models to North Carolina, we determined that chlorophyll a, total phosphorus, and Secchi depth/turbidity, in that order, were the most predictive of designated use status. The models also indicated that the variables that were most predictive of eutrophication were the most predictive of the designated use. This finding is perhaps the most important since it has wide-reaching implications for evaluating predictive nutrient criteria variables in other States. The approaches presented in this chapter provide a scientifically defensible basis for the selection of water quality variables to use as proxies for the designated use.

Then, using the predictive nutrient criteria variables, in Chapter 5 I applied a decision-analytic approach to nutrient criteria setting in North Carolina to offer concrete recommendations for nutrient criterion levels. We developed a nutrient criteria value model that included two submodels, a water quality model and a multiattribute value model. The submodels were parameterized using a combination of water quality data, expert elicitation data, and utility assessments. The outcome of the model is the overall expected value for a criterion level choice; the optimal criterion level would be the choice that maximized the expected value. Using the preferences of North Carolina environmental decision-makers and a criterion variable of total phosphorus, the optimal

criterion level was between 0.03 mg/L and 0.07 mg/L. We were unable to conclusively suggest an optimal total phosphorus level since the expected value did not change much over the range of 0.03 mg/L to 0.07 mg/L, given the model assumptions. The results of this study demonstrate that a multiattribute value or utility analysis provides a novel and practical approach to selecting nutrient criteria in any type of waterbody in any region of the United States.

Together the approach presented in these chapters provide a procedure to establish nutrient criteria variables and levels that is scientifically defensible, protective of the designated uses, and explicitly distinguishes between the science and judgments. In the dissertation I use several case studies to illustrate the approach; however, the method could be applied to any type of waterbody in any region of the United States.

## ***6.2 Future Directions***

In the future, to improve our ability to evaluate and choose nutrient criteria, there are several research directions that I would recommend. First, many nutrient criteria have built in flexibility with the criterion level. For example, instead of setting a criterion where a waterbody is classified as impaired if a single measured value exceeds the criterion level, a significant improvement would include a procedure in the nutrient criteria value model to determine the optimal criterion level if X% of the samples could be exceeded or if the measured values were averaged over a period of time, such as the

growing season. Second, we need to develop trophic state improvement models for all the variables used to predict the eutrophication status. In the water quality model, these variables include total inorganic nitrogen, dissolved oxygen, and turbidity. One method to accomplish this task would be to draw new values for these variables based on the conditional distributions given the modeled improvement values for total nitrogen, total phosphorus, chlorophyll a, and Secchi depth. Third, it would be interesting to explore additional models to predict eutrophication status. One such method would be a Bayesian model that could predict posterior distributions of eutrophication status. Finally, it is essential to better quantify the costs and benefits associated with different standards. Appropriately setting criteria levels requires improved quantification of the costs of research and implementation; this information would allow researchers to better model the costs that would be incurred if a waterbody was classified as impaired. Additionally, it would be useful to consider the monetary non-market benefits of fresh water nutrient reductions. This information would better allow States and Tribes to evaluate nutrient reduction plans and quantify the costs and benefits of different nutrient criteria decisions.

### ***6.3 Pragmatic Suggestions for Immediate Use in the Selection of Nutrient Criteria***

In this dissertation, I presented two approaches to selecting nutrient criteria: a predictive approach using structural equation models and a decision analytic approach using a multiattribute value model. Of these two approaches, the first is less involved than the second. To aid those that are interested in immediate application of the methods presented in this dissertation, I would recommend the following procedure.

First, set nutrient criteria using the predictive approach to nutrient criteria presented in Chapters 2 and 3. Using the state water quality dataset and conducting elicitations with two to three experts on the probability of designated use attainment will provide one with the data necessary for structural equation modeling. Then, following the procedure outlined in Chapters 2 and 3, set the nutrient criterion(a) variable(s) as those that are most predictive of the designated use. Next, plot graphs of the probability of designated use attainment given plausible ranges of the criteria variables; set the levels of the variables as those that correspond to the State's risk of nonattainment of the designated use. Use these variables and their associated levels as nutrient criteria.

Second, evaluate the effectiveness of the criteria for assessing eutrophication-related impairments of the designated use. Collect additional data as necessary to appropriately assess the effectiveness of the criteria. Use this information to

appropriately evaluate the criteria during the triennial water quality standards review.

If it is judged that the criteria are not performing adequately, then proceed to a more methodical strategy to select nutrient criteria using the decision analytic approach to nutrient criteria presented in Chapters 4 and 5. In addition to water quality data, this procedure involves a more extensive expert elicitation, potentially with multiple experts from multiple regions (Chapter 4) and a value assessment of the important attributes (Chapter 5). Next, one needs to develop water quality models to determine the predictive nutrient criteria variables and the eutrophication status, as described in Chapter 4. Then, given the data and water quality models, one can apply a multiattribute value model to determine the specific nutrient criteria that maximize their value, as outlined in Chapter 5. Finally, use the nutrient criteria variables that are most predictive and the levels that maximize their expected value as nutrient criteria.

Ultimately, to protect water quality and maintain designated uses, the nutrient criteria should continue to be reevaluated and modified based on new water quality, expert elicitation, value data, and the models should be updated as necessary. Modify the criteria if the criteria are underprotective or overprotective of eutrophication-related impairments of the designated uses.

## **6.4 Toward an Ideal Method to Set Nutrient Criteria**

Given advances in the past several years both independently by several States and in this dissertation, I would like to propose an approach to set nutrient criteria that strives toward the ideal.

First, ecoregional distinctions should not be the default classification. It is essential to test whether there are regional differences, since different classifications are only useful if they improve the ability to predict impairments. One approach is to apply a quantitative method, such as a classification and regression tree (CART), to determine if there are significant differences that would signal the creation of different classifications using indicators such as ecoregion, land use, or waterbody type.

Second, it is essential to choose criterion variables based on predictive linkages to the designated use. Ideally, these linkages should be formalized and quantified using approaches such as those presented in Chapters 2, 3, and 4.

Third, criterion levels should be set by considering the trade-offs between important attributes and the risks associated with noncompliance of the designated use. In this dissertation I presented two such approaches, one using graphs of the concentration of a predictive nutrient criterion variable and the probability of designated use attainment and the other using a decision-analytic nutrient criteria value model. Of the two approaches, the nutrient criteria value model, presented in Chapter

5, is preferred for its ability to breakdown a complex decision and provide concrete criterion level recommendations based on the preferences of the decision-makers.

Fourth, if multiple variables are used, then it is crucial to consider setting the criteria levels synergistically. The reason to use multiple variables is to capture both the causes and responses to eutrophication. Setting criteria levels by considering the variables independently misses the point of using multiple variables; considering the variables jointly, one can explore developing criterion level indifference curves instead of a threshold.

Fifth, it is foolish to think that any nutrient criteria will be perfect. As a result, after setting reasonable criteria, there needs to be a feedback method to determine false positives. Since the criteria are designed to protect the designated use, I would recommend employing a method such as the one developed in Virginia. If a waterbody is classified as impaired using the nutrient criteria, prior to TMDL listing, perform additional tests to assess whether or not the waterbody is meeting the designated use. If the waterbody is not meeting the use, it is classified as impaired. If the waterbody is meeting the designated use, then site-specific nutrient criteria should be developed. This type of adaptive approach assesses what is important, the designated use, without developing site-specific criteria unless it is needed.

Finally, the nutrient criteria selection decision should be thoughtfully revisited during the triennial review, which is required by the Clean Water Act, to determine if

the nutrient criteria are effectively identifying impaired waters without misidentifying waters that are meeting the designated uses. If the criteria are not performing satisfactorily, then changes should be made using the best science and decision-making judgment to better identify eutrophication-related impairments of the designated uses.

## **6.5 Implications**

Anthropogenic eutrophication is a major source of pollution for many lakes and reservoirs in the U.S. When assessing any waterbody, the major question that arises is whether or not the lake or reservoir is meeting its eutrophication-related water quality goals. Many factors affect whether a waterbody is eutrophied, not just nitrogen and phosphorous loading. As a result, it is essential to develop a method that appropriately considers the complexity of the ecosystem while realizing the data and economic limitations that are encountered by state scientists and decision-makers.

There are few waterbodies that contain the variety of water quality parameters that would be desirable to assess eutrophication. Despite this fact, states need answers regarding whether a lake or reservoir is eutrophied. It is essential, therefore, to develop a method to assess designated use attainment given the current data limitations.

The current USEPA guidance for developing eutrophication criteria is flawed; an alternative method is needed. This research proposes a method to determine the optimal nutrient criterion variables and levels using water quality modeling and

decision analysis. The use of these techniques provides a novel and practical approach to assess eutrophication-impairments of the designated use. Ultimately, I hope this research will establish methodology that is adopted by Tribes, State agencies, and the USEPA as a means to set appropriate water quality criteria that are predictive of designated use attainment.

## **Appendix A: Chapter 2 and 3 Expert Elicitation Protocol**

### ***A.1 Chapter 2 Expert Elicitation Recruitment Letter***

Dear \_\_\_\_\_:

My name is \_\_\_\_\_ and I am a graduate student at Duke University working with Melissa A. Kenney and Dr. Kenneth H. Reckhow. I am writing to provide you with some background information on our project, and the expert elicitation process.

We are conducting a statistical modeling assessment intended to improve methods for the establishment of water quality standards. Specifically, we are addressing the USEPA's national nutrient strategy, which requires states to establish eutrophication-related water quality criteria that are protective of designated uses.

We will be asking you a series of questions based on \_\_\_\_\_ for \_\_\_\_\_. Your role in this process is to help identify a quantitative metric for the designated use statements. Our ultimate goal, following a phone interview, will be to estimate the \_\_\_\_\_ attainment/non-attainment threshold.

Included with this email (as attachments) are:

A few "pre-interview" questions. We will be using your responses to these questions to tailor our interview questions and use your time as efficiently as possible.

Statutory definitions of the designated uses, for your convenience.

Thank you for your time, and I look forward to speaking with you in the near future.

Sincerely,

Nicholas School of the Environment and Earth Sciences

Duke University, Durham, NC

## ***A.2 Chapter 2 Statement of Informed Consent***

You have been invited to participate in an interview as a part of the research for \_\_\_\_\_ Master's Project at the Nicholas School of the Environment and Earth Sciences (advised by Kenneth H. Reckhow and Melissa A. Kenney). The goal of this study is to improve the understanding of the relationship between quantitative nutrient criteria and narrative water quality goal statements.

This interview will last approximately 1-2 hours. During the interview you will be asked to share your opinions on the appropriate quantitative metric for the narrative designated use statements of a waterbody. We will then use the information you provide during the interview to estimate points at which attainment/non-attainment of each designated use occur. There is no right or wrong answer to anything that will be discussed in the interview, and there is no certain answer that the researchers are hoping to hear from you. Results from this interview will be used to develop the following types of research reports: Master's Project, future research protocol, peer-reviewed manuscripts, grant and research reports, and presentations.

You were selected based on your knowledge of the waterbody system and your ability to provide insights regarding appropriate nutrient related water quality indicators. The data generated from the interview process will be recorded by written correspondence, digital recordings of phone and face-to-face communications, taking

copious notes, and by creating formal elicitation reports. The results of the research may be presented in research reports. Access to data will be provided upon request after initial publication. Additionally, the information you provide us is not confidential and the interview and results that you provide us *may* be identified in research reports.

Your participation in this interview is entirely voluntary. You are also free to refuse to respond to any questions and to stop your participation at any time during the interview.

If you have any questions about this research project, please contact the project manager Melissa A. Kenney (m.kenney@duke.edu). If you have any questions about your rights as a research participant, please contact Ms. Lorna Hicks (lorna.hicks@duke.edu), Director of Human Protections Administration at Duke University.

I have read the information in this consent form and have been given the opportunity to discuss it and ask questions.

---

Print name

Sign name

Date

### **A.3 Chapter 2 Preliminary Questions for a Given Region**

Region's Designated Uses:

*select designated use that is most stringent to elicit judgments.*

1. How would you define the designate use?
2. What aspects of the designated use do you consider to be most important?
3. If you had unlimited resources and were able to measure any biological, chemical, or physical variables, what variables would you measure to determine whether or not the designated use was attained?
  - Higher level trophic indicators or other variable that makes sense?
  - Is there any other variables that would perfectly or near perfectly measure the designated use? If yes, what?
  - If multiple variables provided, what would be the single best variable?
  - Why would this variable be ideal to measure designated use?
4. Given the variable that you just identified as ideal to measure the aspects of the designated use, what do you believe is the attainment vs. non-attainment change point level for this variable?
  - Measured value the same as #3.
  - Value provided?
  - Units clear?

- Does it pass the clairvoyant test?
1. Given the variable that you just identified as ideal to measure the aspects of the designated use, what commonly measured water quality variables would you use as a proxy for assessing your identified ideal variable?
    - N
    - P
    - Secchi depth
    - Temperature
    - pH
    - Chlorophyll a
    - What is the relationship among the variables you listed?
    - What is the ecological structure? (conceptual model)
    - Are there any seasonal effects that would change the model?

## A.4 Chapter 2 Expert Elicitation Phase 2

Question:

*Given 100 lakes and reservoirs in the given region, all with identical average levels of these variables in the data row and assuming other factors not listed (e.g., morphological, climatic) vary randomly, how many of the 100 lakes and reservoirs would be in attainment of the designated use?*

Example data rows:

**Table 17: Expert Elicitation Example Data Rows**

<b>Chla</b>	<b>DO</b>	<b>Secchi</b>	<b>TN</b>	<b>TP</b>	<b>DAP (#/L)</b>	<b>ZOOP (#/L)</b>	<b># (out of 100) in .....attainment</b>
1.8	9.2	4.1	201	4.6	0.69	11.78	?
1.4	9.2	5.5	187	6.2	0.70	21.62	?

The expert would answer the question that was stated above in the box labeled "# (out of 100) in attainment."

**Procedure:**

Look at a single data row. Look at all of the values for each of the variables.

These variables were chosen based on your (the expert's) statement regarding measurable eutrophication related variables that are important for assessment of the designated use, using the ideal variable measure of designated use attainment.

Think about the relationship among the variables. Using this conceptual model, make an assessment of the number of lakes that will be in attainment of the designated use (out of 100 lakes).

Consider again the value you (the expert) chose as number of lakes in attainment of the designated use. If 5 more lakes had the exact same values for each of the variables in the data row, would the lake be in attainment of the designated use? If your answer changes, please make the appropriate modifications.

Once you are satisfied with the value chosen, move to the next data row and repeat the process.

When you have finished providing values for each of the data rows, please look through your responses to make sure that you still agree with your response. These values will be used as data in the structural equation models created for the given region.

## ***A.5 Chapter 3 Expert Elicitation Protocol***

Dear \_\_\_\_\_,

I am a doctoral candidate in water quality modeling and decision analysis at the Duke University, Nicholas School of the Environment and Earth Sciences. For my dissertation (advised by Professors Ken Reckhow and Bob Clemen), I am developing a method for establishing nutrient criteria that are predictive of a waterbody's goals, or designated uses. Specifically, my research addresses the USEPA's national nutrient strategy, which requires states to protect designated uses by establishing eutrophication-related water quality criteria. As a demonstration of our method, I am assisting North Carolina in re-assessing their nutrient standards for lakes and reservoirs.

Since there is no existing method for determining whether a waterbody is meeting its designated uses, such as swimmable or fishable, your judgments are needed to help us understand what characteristics of a lake lead to designated use attainment. Using your judgments, coupled with water quality data, we will be able to develop a model that links eutrophication and designated use attainment. (The model and this project do not try to assess compliance of a waterbody with the current water quality standards.) .

For this project, I need to find individuals who are experienced and knowledgeable about North Carolina lakes. You were recommended as an expert by

---

I am writing to find out whether you would be interested in serving as an expert for my study. The process includes two parts, both of which can be completed during a one-day meeting. The first part (approximately 2 hours) will include discussions about eutrophication processes and designated use impairment as well as the use of expert judgments in projects such as this one. In the second part (approximately 1 hour training; 2 hours on your own time), you will provide your judgments about designated use attainment. In this part of the study, I will provide you with data from a number of North Carolina lakes or reservoirs. For each case, you will have multiple measures of eutrophication-related water quality variables. Given these measures, you will be asked to assess the extent of eutrophication and designated-use attainment for that particular lake. We will go through the first few cases together, so that you can work through the remaining cases on your own. In total, this process will take approximately six hours of your time.

After I receive your judgments, I will summarize them in a brief report, which I will send to you for your approval. You will be able at that time to modify or fine-tune your judgments as you see fit.

In return for your efforts, you will be acknowledged in the project's publications, and I will send you, if you wish, a copy of my dissertation and the resulting publications.

I hope that you will agree to participate, because I would enjoy working with you. Please contact me (919-613-8116; m.kenney@duke.edu) if you have any questions.

Sincerely,

Melissa Kenney

## ***A.6 Chapter 3 Expert Elicitation Discussion Questions for the Given Region***

1. What are the mechanisms that lead to eutrophication?

- Indicators
- Nitrogen
- Phosphorous
- Chlorophyll a
- Total Suspended Solids
- Turbidity
- Secchi Depth
- Dissolved oxygen
- pH
- Temperature
- Benthic organism
- Symptoms
- Algal growth
- Reduced clarity
- Reduced oxygen levels
- Fish kills

- Ecosystem change
  - Excessive nutrient loading
  - Chain of events
  - Important factors or major effects of eutrophication in particular region
2. What other variables (non-eutrophication) affect a waterbody's attainment of designated use?
- Variables
  - Toxic algae
  - Sport fish population
  - Fecal coliform
  - Mechanisms
  - Land use
  - Pollutant loading
  - How do the other variables, mechanisms, etc. relate to eutrophication?
  - Fish biodiversity changing with trophic status
  - What does designated use mean? (if necessary)

## A.7 Chapter 3 Expert Elicitation

1. Consider a single data row. Look at all of the values for each of the variables.
2. Given the values for the specific variables in the data row:

*Imagine 100 different lakes with the characteristics specified by the given data row. Of the 100 lakes, how many of the lakes would you expect to fall into each of the following five categories of eutrophication?*

**Table 18: Eutrophication Status Categories**

<b>Category</b>	<b>Description</b>
<b>1</b>	The lakes have: excellent water clarity, no color, very little algae, very low nutrient levels, very high oxygen, no odor, and very healthy, abundant aquatic life.
<b>2</b>	The lakes have: good water clarity, little color, little algae, low nutrient levels, high oxygen, little odor, and healthy, abundant aquatic life.
<b>3</b>	The lakes have: fair water clarity, some color, moderate amounts of algae, moderate nutrient levels, moderate oxygen, little odor, and somewhat healthy, abundant aquatic life.
<b>4</b>	The lakes have: poor water clarity, noticeable color, high algae, high nutrient levels, low oxygen, noticeable odor, and unhealthy, scarce aquatic life.
<b>5</b>	The lakes have: poor water clarity, considerable color, very high algae (likely scums), very high nutrient levels, low to no oxygen, strong offensive odor, and unhealthy, scarce aquatic life or no aquatic life.

**Table 19: Alternative Presentation of Eutrophication Status Categories**

<b>Water clarity</b>	<b>Color</b>	<b>Algae</b>	<b>Nutrient levels</b>	<b>Oxygen</b>	<b>Odor</b>	<b>Aquatic life</b>
Excellent	None	Very little	Very low	Very high	No	Very healthy, abundant
Good	Little	Little	Low	High	Little	Healthy, abundant
Fair	Some	Moderate	Moderate	Moderate	Little	Somewhat healthy, abundant
Poor	Noticeable	High	High	Low	Noticeable	Unhealthy, scarce
Poor	Considerable	Very high	Very high	Low to no	Strong offensive	Unhealthy, scarce or none present

A. Primary Contact Recreation (Swimming, Wakeboarding, Tubing, Water skiing, etc.)

1. Excellent: Greatly exceeds expectations
2. Very good: Exceeds expectations
3. Acceptable: Meets expectations
4. Fair: Below expectations
5. Poor: Far below expectations

B. Secondary Contact Recreation (Fishing, Motorized Boating, Jet Skiing, Canoeing, Kayaking, etc.)

1. Excellent: Greatly exceeds expectations
2. Very good: Exceeds expectations
3. Acceptable: Meets expectations
4. Fair: Below expectations
5. Poor: Far below expectations

## **Appendix B: User Survey Protocol**

### ***B.1 User Survey Recruitment Letter***

June 4, 2005

Dear User Survey Participant:

You are invited to participate in a survey as a part of research for Melissa A. Kenney's doctoral dissertation project (<http://www.duke.edu/mak22>) at the Nicholas School of the Environment and Earth Sciences (advised by Kenneth H. Reckhow). The goal of this study is to better choose water quality indicators and levels that protect the use goals of North Carolina lakes.

You were selected because you are using the lake for one of its recreational goals. The survey will take approximately 3 minutes to complete. In the survey, you will be asked to share your opinions your use of the lake today. Your participation is entirely voluntary. You are free to refuse to respond to any questions and to stop your participation at any time during the survey. If you choose to complete the survey, we will use the survey data to help us assess whether the state is meeting its water quality goals. There is no right or wrong answer to your survey responses, and there is no particular answer that the researchers are hoping you will select.

Your survey responses are anonymous. Your name or contact information is not required or necessary for you to complete the survey. You may, however, provide your

contact information on a separate form if you would like to receive a copy of the final report (available by September 2006) that will be generated using the survey data. The survey data will also be used to answer research questions that will lead to publishable manuscripts. You can keep up-to-date with the project progress at <http://www.duke.edu/mak22>.

If you have any questions about the survey, please contact Melissa A. Kenney (919-613-8133; [m.kenney@duke.edu](mailto:m.kenney@duke.edu)). If you have any questions about your rights as a research participant, please contact Ms. Lorna Hicks ([lorna.hicks@duke.edu](mailto:lorna.hicks@duke.edu)), Director of Human Protections Administration at Duke University.

Sincerely,

Melissa A. Kenney

Ph.D. Student in Water Quality Modeling and Decision Analysis

Duke University Nicholas School of the Environment and Earth Sciences

Enclosure (User Survey)

## **B.2 Lake User Survey**

*Please respond to the following questions for the conditions and your uses today.*

1. What are you using the lake for today (check all that apply)?

- Swimming
- Fishing
- Lake Beauty/Tanning
- Picnicking / Hiking
- Jet skiing
- Canoeing / Kayaking
- Motorized boating
- Wakeboarding / Tubing / Water skiing
- Other (specify)\_\_\_\_\_

2. How often do you use the lake?

- Couple times a week
- Once a week
- Twice a month
- Once a month

Occasionally

First time

3. What qualities of the water do you believe are important to be able to use the lake (check all that apply)?

High clarity

Water temperature

Little water odor

High oxygen level

Little water color

No algal scums

Sport fish populations

Little sediment (dirt) in the water

Other (specify) \_\_\_\_\_

4. The water of the lake is crystal clear today.

Completely agree

Agree

Neutral

Disagree

\_\_\_ Strongly Disagree

5. What is the color of the water?

\_\_\_ Blue

\_\_\_ Green

\_\_\_ Brown

\_\_\_ Brownish / Green

\_\_\_ Other (specify)\_\_\_\_\_

6. How would you describe the condition of the lake, in regards to the algae, today?

\_\_\_ The water is crystal clear. There are no apparent problems.

\_\_\_ It's not perfectly clear; there is a little algae.

\_\_\_ There is algal growth; water appears green, yellow, or brown from algae.

\_\_\_ There are high levels of algal growth limiting water clarity or causing odor.

\_\_\_ Severe water impacts from algal growth causing massive algal scums on the lake or washed up on shore, strong offensive odor, or fish kill.

\_\_\_ Other impacts, not algal related (specify)\_\_\_\_\_

7. How would you describe the condition of the lake, in regards to the sediment, today?

\_\_\_ The water is crystal clear. There are no apparent problems.

\_\_\_ It's not perfectly clear; there is a little sediment.

\_\_\_ There is obvious sediment; water appears brown from sediment.

\_\_\_ There is a large amount of sediment limiting water clarity.

\_\_\_ Severe water impacts from sediment; the water appears and feels like muddy water.

\_\_\_ Other impacts, not sediment related (specify) \_\_\_\_\_

8. The conditions of the lake are perfect for my use(s) today.

\_\_\_ Completely agree

\_\_\_ Agree

\_\_\_ Neutral

\_\_\_ Disagree

\_\_\_ Strongly Disagree

9. How would you rate the conditions of the lake based on your experiences today?

a. Quality

\_\_\_ Excellent

\_\_\_ Very good

\_\_\_ Acceptable

\_\_\_Fair

\_\_\_Poor

\_\_\_N/A

b. Lake Beauty

\_\_\_Excellent

\_\_\_Very good

\_\_\_Acceptable

\_\_\_Fair

\_\_\_Poor

\_\_\_N/A

c. Swimming or Wakeboarding / Tubing / Water skiing

\_\_\_Excellent

\_\_\_Very good

\_\_\_Acceptable

\_\_\_Fair

\_\_\_Poor

\_\_\_N/A

d. Fishing

\_\_\_Excellent

\_\_\_Very good

\_\_\_Acceptable

\_\_\_Fair

\_\_\_Poor

\_\_\_N/A

e. Motorized Boating or Jet Skiing

\_\_\_Excellent

\_\_\_Very good

\_\_\_Acceptable

\_\_\_Fair

\_\_\_Poor

\_\_\_N/A

f. Canoeing or Kayaking

\_\_\_Excellent

\_\_\_Very good

\_\_\_Acceptable

\_\_\_Fair

\_\_\_Poor

\_\_\_N/A

10. What factors, if any, are impacting or limiting your use of the lake today (check all that apply)?

\_\_\_ Poor clarity

\_\_\_ Water temperature

\_\_\_ Water odor

\_\_\_ Low oxygen level

\_\_\_ Water color

\_\_\_ Algal scums

\_\_\_ Few sport fish populations

\_\_\_ Sediment (dirt) in the water

\_\_\_ None

11. If you went fishing, how many fish have you caught today?

\_\_\_0

\_\_\_1

\_\_\_2

\_\_\_3-4

\_\_\_5-6

\_\_\_more than 6

\_\_\_N/A

12. If you went fishing, what type and how many of each fish have you caught today (if applicable)?

\_\_\_ Crappie

\_\_\_ Catfish

\_\_\_ Walleye

\_\_\_ Bass

\_\_\_ Bluegill

\_\_\_ Shad

\_\_\_ Sunfish

\_\_\_ Perch

\_\_\_ Trout

\_\_\_ I don't know

\_\_\_ N/A

\_\_\_ Other (specify)\_\_\_\_\_



## Optional Demographic Information

A. What is your age?

under 18

18-25

26-35

36-49

50-65

65 or older

B. What is your gender?

Male

Female

C. What is your race or ethnicity?

Caucasian/White

African American

American Indian

Hispanic

Pacific Islander

Asian

\_\_\_ Other (specify)\_\_\_\_\_

D. What is the highest level of education you have completed?

\_\_\_ Some High School

\_\_\_ High School degree

\_\_\_ Some College

\_\_\_ College degree

\_\_\_ some Graduate School

\_\_\_ Graduate degree

E. Where do you live?

\_\_\_ On lake INSERT

\_\_\_ INSERT TOWN/CITY

\_\_\_ INSERT REGION

\_\_\_ North Carolina

\_\_\_ United States

\_\_\_ outside United States

F. Do you participate in an association related to the lake, such as homeowners' organization, friends of the lake, fishing club, etc.?

\_\_\_ No

\_\_\_\_ Yes (specify) \_\_\_\_\_

## Appendix C: Expert Elicitation

### *C.1 Blue Ridge: Jerry Miller*

Expert Elicitation Discussion for the North Carolina Blue Ridge Ecoregion

Dr. Jerry Miller

March 28, 2006

Summarized by: Melissa A. Kenney

#### What are the mechanisms that lead to eutrophication?

- Nutrients are usually not a problem for reservoirs in the Blue Ridge Ecoregion. In general, the lakes in this region are oligotrophic because they are nutrient poor.
- The primary pollution problem in the reservoirs is from sedimentation, which leads to water clarity issues as well as a loss in water depth and reservoir capacity.
- Land use is the most significant source of sediment. In the past decade, there has been a 4 to 5 fold increase in sedimentation rates as a result of development in this area.
- Potential sources of nutrients include:

- Agriculture (Christmas tree farms, timber, feedlots, etc.)
  - Urban and residential development
  - Wastewater treatment plants (not very significant)
  - Faulty septic tanks
  - Straight piping
- Phosphorous tends to be a more significant issue than Nitrogen, primarily because it can be bound to sediments and enters the reservoir with the sediments.
  - Increased total phosphorous levels cause an increase in algal and cyanobacteria growth. This increased primary productivity growth contributes to a decrease in water clarity, an increase in turbidity, and a decrease in dissolved oxygen levels.
  - Eutrophication can also potentially change the diversity and productivity of the various algal species.

### **Eutrophication Continuum**

Scale of 1 (highly oligotrophic) – 10 (highly eutrophic)

- Average: 3
- Range: 2 - 5
- Best achievable improvement: approximately 1 level improvement. The lakes couldn't go back to a pristine state.

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

### Designated Use, Primary Contact Recreation

The following are other variables that affect a waterbody's attainment of primary contact recreation uses:

- Water clarity
- Odor
- Taste
- Fecal coliform
  - These problems are mostly localized as a result of straight piping, or livestock.

### Designated Use, Secondary Contact Recreation

The following are other variables (constituents) that affect a waterbody's attainment of secondary contact recreation uses:

- Other Chemicals
  - Toxic metals
  - Organic compounds
  - Industrial waste

- Petroleum
- Pesticides
- Accumulation of toxic materials
  - Mobilized during anaerobic conditions (does not apply to all contaminants)
  - Unpredictable flushes from weather conditions
- Can potentially affect anglers that consume their caught fish
- Nonpoint source reduction of chemicals can be a substitute means to reduce other pollutants (e.g, sediment)
- Algae stains on fiberglass boats (How did I say this influenced attainment of a designated use?; it would seem to be a response to poor water quality)

**Other comments:**

- There is occasionally a fundamental conflict between primary and secondary contact recreation since many of the uses are incompatible.
- It could take quite a while to accomplish change in a reservoir – up to a couple decades.
- In this area, many fishermen want bigger fish, but do not want larger fish if it is due to higher nutrient loads that decrease water quality.
- Turbidity is the primary problem with designated use attainment.

- The nutrient and chlorophyll-a numbers seemed pretty high for this area. In fact, most I would consider anomalous. After I finished filling out the booklet, I looked up some data on local lakes that had been collected for the state back in the 1970s. Their published numbers for this area were more in-line with what I had expected (which gave me a bit of confidence in what I was doing). You had mentioned that the some of the data rows were observations from the Blue Ridge. After you finish your study, it would be nice to see which rows were from here and from which lakes. My colleagues and I have been working on the assumption that nutrients are not a significant issue in the mountains. However, given these observations, we may need to rethink that assumption.
- I think I have figured out what bothered me about the data set as we were going through the practice examples. There is a lack of what one might call structure in the data rows. That is, you would expect to see some kind of relationship between the variables. Here, of course, it would be impossible with one observation to see if any correlations exist. However, it could be expected on the basis of previous work and the way in which trophic levels have been categorized that when one variable such as chlorophyll-a is high (hypertrophic), that secchi depth would be low, or when secchi depth is low that either chlorophyll-a or turbidity would be high, etc. Such simplistic relationships don't seem to exist. Nor does there seem to be any relationship between the drivers

and the response variables. This, then, makes it difficult to determine trophic status or the attainment of designated uses on a consistent basis (from one data row to the next). Perhaps this was part of the point – that different combinations of variables can lead to a similar distribution, but it would be more satisfying if I could have listed out a series of criteria or relationships around which the various distributions could be based and which could be consistently applied to each of the data rows. I suspect that others who look at the data and who are more familiar with lacustrine processes will be more successful in this regard.

- The apparent lack of data structure, however, raises the question as to why this is the case. Here is the problem as I see it. We are looking at one observation and assessing the distribution of say trophic level across the landscape for 100 lakes. That observation is for one instant in time. However, if the sample was collected in the spring, you would get one spatial distribution, if it was collected in the summer, you would get a very different distribution because the temporal variations between the impoundments differ. You must, as instructed, assume that each data row represents the mean condition of a lake which describes the variations in a given parameter through time. I suspect, however, that if the data rows actually represented the mean conditions through time, rather than an observation at a given point in time, the relationships between parameters would be more in line with what I expected for this region. The point of all of this is

that the exercise really highlights the need to examine the data structure of individual lakes in order to designate their trophic status or determine whether they are meeting a specific designated use. Presumably, the experts should already know what the data structure for a specific ecotone is, but as mentioned earlier, many of the data rows appeared anomalous if the data were considered to represent an average for the lake, making it difficult to know how to create the various distributions. I don't know if there is a solution to this, but perhaps it is something to think about.

#### **How did you make your judgments?**

- Focused on total phosphorous, chlorophyll a, Secchi depth, and turbidity.
- Unfamiliar with the nitrogen measurements. Placed less weight on dissolved oxygen.
- I found that while assigning numbers to the attainment of designated uses that I primarily used Chlorophyll a and measures of water clarity because of their control on what people actually experience (taste, odor, scum, particulate content, etc.). I am sure you will find this in the data.
- Other than more productive lakes potentially being more beneficial to secondary contact recreation (i.e., fishing), the parameters that defined the distribution for primary and secondary contact recreation were essentially the same. I think you

will find that the two distributions are highly correlated, although offset from one another.

## **C.2 Blue Ridge: Barbara Wiggins**

**Expert Elicitation Discussion for the North Carolina Blue Ridge Ecoregion**

**Barbara Wiggins**

**May 10, 2006**

**Summarized by: Melissa A. Kenney**

### **What are the mechanisms that lead to eutrophication?**

- There's not a lot of difference between eutrophication impairment issues in the different North Carolina ecoregions. There are a couple of notable differences, though:
  - The Blue Ridge ecoregion has reservoirs of different temperatures and certain reservoirs can have trout.
  - The lakes in this region are located in the headwater region of the state.
  - Most of these waters are not buffered, which can lower the lake's pH.
- The majority of the nutrient sources in this region are from nonpoint sources.

These sources include:

- Sedimentation and erosion (major source)
- Agriculture
- Landscaping and fertilizing

- Septic tanks or sewer lines
- There are also point sources that can contribute nutrients to a waterbody.
  - Treatment plants
  - Atmospheric deposition
    - This area receives, on average, 80" per year of deposition.
- Increased nutrient levels cause an increase in the plant community. This increased plant growth is from both blue/green algae and aquatic weeds. The increased plant community growth can cause an increase in the dissolved oxygen deficit. Increased plant biomass can lead to fish kills.
- Shallow lakes have higher flushing rates.

### **Eutrophication Continuum**

Scale of 1 (highly oligotrophic) – 10 (highly eutrophic)

- Median: 3
- Range: 1 -- 5
- Best achievable improvement: improvements may take a large amount of time to be realized because of a lake's residence time. Best management practices lead to incremental changes; point sources can lead to noticeable improvements. If improvements were implemented, it would take at least 10 years to detect a change.

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

### Designated Use, Primary Contact Recreation

The following are other variables that affect a waterbody's attainment of primary contact recreation uses:

- Odor
- Bacteria
  - Higher nutrient levels are typically associated with higher bacteria levels
  - Can cause skin rash or other health effects
- Geese or duck populations
  - Can be a problem in smaller waterbodies
  - May become a factor with avian flu
- Noxious algal blooms
  - Can be toxic
  - Concerns of ingestion making children sick
- Aesthetics
  - Dislike a slimy feel from algal scums
  - Water color

- Invasive plants
  - Increased growth from higher nutrient waters
  - Not fun to swim through

## Designated Use, Secondary Contact Recreation

The following are other variables that affect a waterbody's attainment of secondary contact recreation uses:

- Aesthetics
  - Boaters don't like algal scums on their boats
  - Lakes with weeds emerging don't look as nice
- Aquatic weeds
  - They can wind around boat propellers
- Odor from algal blooms
- Noxious algal blooms
  - Can be toxic
- Fish health
  - Can deteriorate in high nutrient conditions
  - Can cause lesions or parasites
  - Fish kills – discourage fishing and swimming in general
- Sedimentation

- Decreases water depth
- Can accelerate succession
- Mucky sediments decrease swimming and access enjoyment when you sink into muck as you walk into the lake

**Other comments:**

- Most nutrient impacts in the lakes in this region are due to the shallowing of the reservoirs.
- The reservoirs in this region are, in general, nutrient poor; therefore, they could absorb more nutrients before there would be eutrophication effects.
- A lot of the reservoirs were created for drinking water. Most of the mountain reservoirs were built for aesthetics or recreation and not drinking water. Most use groundwater and river intakes, with some municipal reservoirs.
- The lakes are not fertilized, but nutrient inputs are not considered a problem.
- Some people desire more nutrients in a lake to increase the aquatic biomass.

**How did you make your judgments?**

- Nitrogen, phosphorous, turbidity, and Chlorophyll a. First cut, looked at nutrients and chlorophyll a. Looked at all the variables. Dissolved oxygen was less important, used more as a check.

- Chlorophyll a – is there a lot of algae and is it a visible problem?
- Primary and secondary contact recreation – primarily used turbidity, Secchi depth, and Chlorophyll a. Nutrients didn't matter if there was not a noticeable problem.

### **C.3 Piedmont: Todd Kennedy**

**Expert Elicitation Discussion for the North Carolina Piedmont Ecoregion**

**Todd Kennedy**

**June 5, 2006**

**Summarized by: Melissa A. Kenney**

#### **What are the mechanisms that lead to eutrophication?**

- The lakes in the Piedmont ecoregion are man-made.
- The watershed in this region is developed or developing. This development leads to increased runoff and pollutants, particularly nutrient and sediment, loading.
- The lakes are managed for multiple uses.
- Sediment and algae are linked because nutrients can be attached to sediments. An increase in nutrients promotes algal growth. The lake's residence time and the associated hydraulics can also affect algal growth.
- Some algae are more desirable as a food source than others. The algae speciation can affect zooplankton growth, which then affects the higher trophic organisms.

- If there is an excess of algal growth or algal blooms, there can be hypoxic or anoxic conditions in the lake. This can impact fish through increased mortality, stress, susceptibility toward disease, and changes in the community structure.
- Nutrients and sediments also impact transparency. Water clarity, or transparency, can be reduced from an influx of fine sediments. In the Piedmont ecoregion there is naturally a higher amount of fine, clay particles. Additionally, there is a large amount of development that increases runoff of these particles.
- Soil may inhibit algal growth when it enters a waterbody by reducing water clarity, which reduces light availability throughout the water column.
- Transparency can have a big effect on the user's perception of designated use enjoyment.
- Human impacts and sources have a larger impact on the lake systems than the natural sources. The specific sources are lake specific. Additionally, some lakes have different watershed arms that mean there is significant spatial variability within the waterbody and the sources that affect the waterbody.
- The primary anthropogenic source in this region is residential, commercial, and urban development. This source has a greater export of nutrients per area than agriculture. It can be caused, in part, from lawns and build-up of impervious areas.

- Additional sources include: agriculture, confined animal feeding operations (CAFOs), atmospheric deposition, wastewater treatment plants (WWTP), and automobiles.
- Nonpoint sources are the largest source of eutrophication nutrients.
- There are few direct nutrient discharges to a lake, most of the nutrient inputs are from the tributaries.

### Nutrient speciation

- Both nitrogen and phosphorous contribute to algal growth. Silica is also a nutrient that is occasionally discussed as potentially limited, but it is not much of a limiting factor, if any, in North Carolina.
- What nutrient limits algal growth depends on the lake. Too often people assume that lakes are phosphorous limited, but some lakes are nitrogen limited. Just assuming that the lakes are phosphorous limited is not necessarily managing the lake system properly.
- The nutrient limitation also varies between and within lakes.
- Ultimately, both nutrients need to be reduced.

### Eutrophication Continuum

Scale of 1 (highly oligotrophic) – 10 (highly eutrophic)

- Median: 7
- Range: 4 -- 10
- Best achievable improvement: there is only so much nutrient reduction feasible in this ecoregion. Therefore, the median improvement would be a 5, or mesotrophic.

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

Designated Use, Primary Contact Recreation

The following are other variables that affect a waterbody's attainment of primary contact recreation uses:

- Sediments
- Water clarity
  - Aesthetic concerns
- Floating debris
- Build-up of hydrocarbons
  - An oil film from motorboats
- Dead fish
- Fecal coliform
  - The user will not know whether fecal coliform is present in the water.

- Malfunctioning septic tanks are one of the main sources that contribute to this problem.
- There are also natural sources of fecal coliform, such as water fowl and wildlife.
- Toxic algae
  - May not be a major variable for primary contact recreation, but could affect the water supply.
  - Algae build-up, in general, is undesirable.

### Designated Use, Secondary Contact Recreation

The following are other variables that affect a waterbody's attainment of secondary contact recreation uses:

- Sediment
  - May affect aesthetics
- Floating debris
- Fecal coliform
  - Can cause odor and health problems
- Build-up of hydrocarbons
- Fish species

- Want fish that should be present in warm-water fisheries. There should be a balance within the eutrophic condition. Fishermen want nutrients to benefit the fishery; they don't want too many to be taken out.
- Algal mats or blooms
  - Can cause odor problems

**Other comments:**

- Lakes are so different because of between and within lake variability that it is difficult to give assessment. Also because of the spatial variability it is difficult to assign criteria.
- In these lakes, a lot of the eutrophication problems can be addressed by reservoir operation. Reservoir operation can change the residence time of the lake and the discharge water can be taken from the top instead of the bottom. This does not address, however, a significant part of the answer.
- Water supply is also a use of these lakes. For water supply, certain algae contribute to taste and odor problems; these algae can be connected to toxic algae.
- There is a conflict between primary and secondary uses. Those that are connected more to the aesthetics of the lake would like a lake to be in a more oligotrophic status. Fishermen, on the other hand, desire more eutrophic

conditions for their use. Water supply uses want to minimize motorized boating to minimize the treatment costs from the pollutants that occur from motorized boating.

- Also, motorized boating and non-motorized boating can be conflicting uses.

## **C.4 Piedmont: Andrew McDaniel**

**Expert Elicitation Discussion for the North Carolina Piedmont Ecoregion**

**Andrew McDaniel**

**June 19, 2006**

**Summarized by: Melissa A. Kenney**

### **What are the mechanisms that lead to eutrophication?**

- Eutrophication is an issue in the Piedmont ecoregion, particularly in the larger water supply reservoirs. These types of waterbodies are used by a large number of people, have multiple uses, and have a high economic value (tourism, property, power generation, etc.).
- Nitrogen and phosphorous are the two limiting nutrients that drive eutrophication.

### **Sources of Eutrophication**

- Nutrients can enter a waterbody from a variety of locations. These include:
  - Stormwater runoff, both from the roadway and urban areas
    - There is limited knowledge of the contribution of nutrient loading from this source

- This source can be considered both a point and non-point source pollutant, depending on the group that defines the source. For example, USEPA states that stormwater is a point source, where as other groups classify it as a non-point source.
  - Atmospheric deposition
  - Agriculture
    - Non-point source pollution source, so it is difficult to manage
  - Wastewater treatment plant discharge
- There is a temporal aspect to nutrient loading. This temporal component adds problems from a management perspective because it is unclear what the “true” or source of the pollutant that can be regulated.

### Eutrophication Processes

- Increased nutrients cause an increase in nuisance algal blooms. These algal blooms can lead to algal scums, taste and odor problems, and toxic algae.
  - Additionally, a change in the algal assemblages can put the ecosystem out of balance which can cause elevated levels of nuisance algal species.
- Increased algal production can lead to elevated dissolved oxygen levels, followed by a decline in dissolved oxygen levels as oxygen is consumed during the algal decay process.

- The lower oxygen levels can eventually lead to stress or death of benthic organisms and fish.

### **Eutrophication Continuum**

Scale of 1 (highly oligotrophic) – 10 (highly eutrophic)

- Median = 7
- Range = 5 -- 9
- Best achievable improvement: 6, the high end of mesotrophic to the lower end of a eutrophic state

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

Designated Use, Primary Contact Recreation

The following are other variables that affect a waterbody's attainment of primary contact recreation uses:

- Human pathogens
  - Fecal coliform
  - Other viral or bacterial pathogens
- Toxic algae

- This is not really a problem in this region, but, in theory, it could affect attainment of the use.
- Taste and odor problems
  - Not a common problem
- Aesthetics
  - Algal scums or other types of scums
  - Sedimentation
    - Affect water clarity and turbidity
    - Can potentially be correlated with higher levels of pathogens, leading to human health effects
  - Foam from stormwater discharge
    - Not a common issue for lakes in this region
  - Water color
    - Not a common issue for lakes in this region
- Aquatic weeds, such as hydrilla

### Designated Use, Secondary Contact Recreation

The following are other variables that affect a waterbody's attainment of secondary contact recreation uses:

- Aquatic weeds, such as hydrilla

- These weeds can get caught in motor boats
- Human pathogens
  - Fecal coliform
  - Other viral or bacterial pathogens
- Toxic algae
  - This is not really a problem in this region, but, in theory, it could affect attainment of the use.
- Taste and odor problems
  - Not a common problem
- Aesthetics
  - Algal scums or other types of scums
    - Particularly floating mats of algae that make boating difficult
  - Sedimentation
    - Affect water clarity and turbidity
    - Can potentially be correlated with higher levels of pathogens, leading to human health effects
  - Foam from stormwater discharge
    - Not a common issue for lakes in this region
  - Water color
    - Not a common issue for lakes in this region

- Low dissolved oxygen levels
  - Affects fish species
- Fish health
  - Only a problem when there are significant eutrophication or other pollution problems
  - Higher nutrients are desirable for fishing because it increases fish biomass
- Fish biodiversity and sport fish
  - Want to assure appropriate diversity to support recreational fishing

**Other comments:**

- From a use sustainability standpoint, the lakes in the Piedmont region are not so bad.
- The best achievable improvement is effected by largely unchangeable conditions such as the residence time and the nutrients in the lakebed sediments.
- Additionally, the use attainment must consider both the management goals and the cost of achieving those goals.
- There is not a huge distinction between variables that would affect designated use attainment for primary contact recreation vs. secondary contact recreation.

- There is an inherent conflict between primary and secondary contact recreational uses. The primary contact users desire more oligotrophic conditions, where as the secondary contact recreation users don't mind or desire more eutrophic conditions.

## ***C.5 Piedmont: Samuel C. Mozley***

**Expert Elicitation Discussion for the North Carolina Piedmont Ecoregion**

**Dr. Samuel C. Mozley**

**March 3, 2006**

**Summarized by: Melissa A. Kenney**

### **What are the mechanisms that lead to eutrophication?**

- Excess nutrients are introduced primarily into reservoirs through point source pollution from wastewater treatment and nonpoint source runoff from suburban development and agricultural land.
- Though the concept of eutrophication is the same regardless of the location, in the Piedmont Ecoregion, the process and symptoms manifests itself differently in the upper reaches vs. the lower reaches of the lakes.

### **Upper reaches of the reservoir**

- If there are eutrophication problems in a lake, they are predominantly expressed in the upper reaches of the lake.
- More often than not, when the nutrients enter the waterbody, they are bound to clay particles. In particular, phosphate and ammonium exhibit this phenomenon.

- There is a complicated exchange process between the clay and algae that results in a more constant algal community instead of the more "boom and bust" events. As a result, the excess nutrients can result in invisible algal blooms.
- Though the upper reaches tend to be algae rich, there are rarely noxious algal blooms in the Piedmont Ecoregion.
- Additionally, algae only slightly affect water color; the more dominant factor in water color is suspended clay particles.
- Nutrient speciation
  - Ammonium more likely to be absorbed by clay
  - Orthophosphates are dynamic, and thus is not very useful as a measurement
  - Total phosphorous gives about all the information available since the phosphorous cycle is in constant flux on short time scales
- In general, the impact of eutrophication in the upper reaches is fairly small. The eutrophication providing both positive and negative effects.
- Positive effects
  - In the upper reaches of the reservoir, the sport fish are larger and more concentrated, making them popular fishing areas.
- Negative effects

- The byproduct of algal production is the secretion of dissolved organic matter into the water column, which fosters bacterial growth. These bacteria can cause lesions on the fish or fish disease.
- Secondly, if there is water intake in this region then there may be taste and odor problems or additional costs for filtration.

#### Deeper (lower) regions of the reservoir

- In general, there is not a problem with eutrophication in the deeper reaches of the reservoir.
- A symptom typically attributed to eutrophication is oxygen depletion below the thermocline. However, oxygen depletion in this region is unavoidable and happens regardless of eutrophication.
- In the deeper regions, oxygen depletion does not occur because of the classic effect of self-eutrophication. Self-eutrophication is where the depletion of oxygen results in massive cycling of phosphorous. Additionally, with self-eutrophication there will still be visible signs of eutrophication, even if the phosphorous inputs are drastically reduced.
- The main problem with oxygen depletion is that it reduces the number of desirable large sportfish, such as striped bass and striped bass hybrids. These sportfish do not do well when the cooler water is oxygen poor. However, these

fish are not native – they are stocked, protected, and regulated – thus, they are not a good measure of whether the water quality is appropriate to support native wildlife.

- Reducing nutrient demand would not have an effect on deoxygenation of the waters in these lower reaches. The reason for the deoxygenation is because waters are warm on the bottom, which supports higher levels of bacterial activity.

### **Eutrophication Continuum**

Scale of 1 (highly oligotrophic) – 10 (highly eutrophic)

- Upper reaches (depth < 5 m) = 5 – 6
- Lower reaches = 2 – 3
- Best achievable improvement: could not necessarily do much better without massive cost and reduction investments, particularly for improved designated use attainment

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

### Designated Use, Primary Contact Recreation

The following are other variables that affect a waterbody's attainment of primary contact recreation uses:

- Fecal coliform
  - Can be effected by algal blooms
  - Possible that eutrophication can ultimately cause an increase in beach closings
- Increases of undesirable organisms such as a natural, nonstinging jellyfish
- Noxious algae or Blue-green algae (cyanobacteria)
  - Flourish in warm waters
  - Can take advantage of imbalances of P:N ratio because they are N fixers
  - Greater likelihood of toxic algae

### Designated Use, Secondary Contact Recreation

The following are other variables that affect a waterbody's attainment of secondary contact recreation uses:

- Other Chemicals
  - Toxic metals

- Organic compounds
- Industrial waste
- Petroleum
- Accumulation of toxic materials
  - Mobilized during anaerobic conditions
  - Unpredictable flushes from weather conditions
- Effects anglers that consume their caught fish
- Nonpoint source reduction of chemicals can be a substitute means to reduce other pollutants
- Algae stains on fiberglass boats

**Other comments:**

- There is a fundamental conflict between primary and secondary contact recreation since many of the uses are incompatible.
- Eutrophication is a secondary means of classification; food chain effects, instead, are more important than eutrophication in terms of assessing designated use attainment. Food chain effects control algal productivity. The different types of algae affect the types of algal grazers and the concentration of algae. The balance of the overall productivity and algal growth rates effect angling through the type of fish present.

## **How did you make your judgments?**

### **Eutrophication**

- First, I looked at the chlorophyll *a* measurement. Then, I considered the other variables, such as turbidity, Secchi depth, and nitrogen levels. For total phosphorous, I determined whether the total phosphorous levels could support the algal growth.

### **Secondary contact recreation**

- To make my assessment, I weighted angling as a more important use than boating.

## **Is there any data that would have been useful to make your judgments?**

- Fish data: fish survey from anglers or total fish biomass
- Algal speciation
- Epilimnetic dissolved oxygen levels

## **C.6 Piedmont: Chris Roessler**

**Expert Elicitation Discussion for the North Carolina Piedmont Ecoregion**

**Chris Roessler**

**June 5, 2006**

**Summarized by: Melissa A. Kenney**

### **What are the mechanisms that lead to eutrophication?**

- All of the lakes located in the Piedmont ecoregion are man-made.
- The trophic status of the lakes in this region is primarily eutrophic. This occurs because:
  - The lakes have sediment loading that reduces the volume of the lake when it settles out. This can cause water storage problems and concentrate the pollutants in the lake.
  - There is a decent amount of nutrients input into the lakes.
  - The land uses around the lakes are primarily developed for urban growth, farming, and rural residential development.
- Nutrient loading to the lakes in the Piedmont ecoregion is increasing.
- The primary source drivers of nutrient inputs are urban development and rural residential development.

- Other nutrient sources include automotive exhaust, atmospheric deposition onto impervious surfaces, and poorly managed fertilizer use in urban areas.

### Eutrophication process

- Nutrients fuel the eutrophication process. Nutrients, such as phosphorous, can be weakly attached to sediment or clay particles. These nutrients transform into a bioavailable state.
- Increased bioavailable nutrient levels lead to increased algae levels. Certain algae, such as blue-green algae, are nitrogen fixers. Other than nitrogen and phosphorous, algae also need other nutrients. These algae are located primarily in the photic zone of the lake.
- In the daylight, algae photosynthesize in daylight, taking in carbon dioxide and emitting oxygen. During the non-daylight hours, the algae respire carbon dioxide and consume oxygen. Additionally when algae die, bacteria decompose them; these bacteria consume oxygen and emit carbon dioxide.
- Algae are the lowest organism on the food chain. Zooplankton graze on the algae. This community structure affects the fish present. Since these are warm-water fisheries, we want nutrients in the waters to support typical warm-water fishery species, such as bass.

- The higher trophic organisms, such as macroinvertebrates and fish, are affected by both oxygen and nutrients.
- Lakes also have temperature gradients.
- One would expect higher oxygen levels in the epilimnion and lower oxygen levels in the hypolimnion. The one exception is that during the spring and fall turnover, there is mixing throughout the water column.
- Both the algal community and the sediment load affect the photic zone depth by increasing the turbidity and decreasing water clarity. This reduced water clarity can affect lake users' perception of water quality.
- Sediment can affect aquatic habitat and submerged aquatic vegetation because it can cover the bottom substrate.

### **Eutrophication Continuum**

Scale of 1 (highly oligotrophic) – 10 (highly eutrophic)

- Range: 7 -- 8
- Best achievable improvement: could keep the lakes from becoming hypereutrophic, extend the life of the lakes, reduce or maintain treatment costs, and potentially increase more diverse aquatic biotic community. Improvements would primarily be maintenance to stay at the status quo; although, in some

lakes there may be some improvement, at least there would be fewer extreme cases.

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

**Designated Use, Primary Contact Recreation**

The following are other variables that affect a waterbody's attainment of primary contact recreation uses:

- Weed growth
- Blue-green algae
  - Toxic algal blooms
  - These are a rare occurrence
- Water clarity
  - Tied to user's perceptions
- Fecal coliform
  - Associated indirectly with nutrient sources
  - Levels are usually higher near coves, inlets, and tributaries

## Designated Use, Secondary Contact Recreation

The following are other variables that affect a waterbody's attainment of secondary contact recreation uses:

- Weed growth
- Fish population decline
  - This occurs when the water is oxygen poor or eutrophication is really bad
  - Most fish like lots of nutrients
- Fish species
  - These lakes are warm-water fisheries so ideal species are those that thrive in those waters, such as bass, "pan" fish, brim, and bluegill.
- Appropriate fish habitat
  - It is important to have some logs or other habitat by the banks to provide shelter.
  - Also, want a variety of lake depths so that there are places for the fish to migrate.
- Water clarity
  - Fish will have better visibility
  - Tied to user's perceptions
- Blue-green algae and fecal coliform
  - These pollutants have less of an impact on this use

**Other comments:**

- In general, more polluted waters are more nutrient rich.
- Right now, for lakes in the Piedmont ecoregion, the nutrient levels are usually at an acceptable level for both primary and secondary contact recreation. Though a fishing use may be sustainable in waters that are more nutrient-rich than a swimming use, it is not the case that where fishing is good, the swimming is bad.
- Most of the lakes are used for drinking water. You can treat any water to a drinkable level, but the more polluted it is the more you will have to treat it. Therefore, less polluted water costs less money to make drinkable. As a result, it is important to weigh pollution prevention vs. a treatment cure for water treatment.
- Most drinking water reservoirs are managed for multiple uses, including primary and secondary contact uses. The lakes are also used to manage water flow throughout the year.

## **C.7 Piedmont: Kathy Stecker**

**Expert Elicitation Discussion for the North Carolina Piedmont Ecoregion**

**Ms. Kathy Stecker**

**May 23, 2006**

**Summarized by: Melissa A. Kenney**

### **What are the mechanisms that lead to eutrophication?**

- Eutrophication in the Piedmont Ecoregion is a result of nutrient enrichment from cultural eutrophication. These sources can be from either point sources or nonpoint sources.
- Point source pollutants include: wastewater treatment plants, industrial plants, municipal stormwater, and construction or industrial runoff.
- Nonpoint source pollutants include: septic tanks, residential and agricultural fertilizers, and sedimentation.
- Nutrients enter the waterbody primarily through tributaries and the streamline and the shoreline.

### **Limiting Nutrients**

- When nutrients enter the waterbody, they are bioavailable when they enter or transform to a bioavailable state.

- I believe all Piedmont lakes are phosphorous limited; I don't believe that any of the lakes are nitrogen limited.
- Nutrients only become bad when there are too many nutrients in the waterbody. These elevated levels of nutrients can cause nuisance levels of phytoplankton, visible algae and/or a poor mix of algal species.
- Nuisance algal growth can be followed by phytoplankton die-off. This can lead to a decrease in oxygen levels, and potentially fish kills.
- Prior to seeing fish kills, it is likely that there would be a change in the phytoplankton community structure, which would cause a change in the zooplankton community structure. The change in zooplankton structure would cause a change in the fish community structure.
- Additionally, phytoplankton growth can cause a large diurnal fluctuation of dissolved oxygen and pH.
- In general, phytoplankton growth in very eutrophic lakes in this region is not limited by nitrogen or phosphorous. It is limited by light, space, or micronutrients.
- Lakes in this region are deep enough that they would stratify so there would be some naturally anoxic conditions. This hypolimnic oxygen depletion, can be exasperated by phytoplankton growth, but is largely the result of stratification.

## Eutrophication Continuum

Scale of 1 (highly oligotrophic) – 10 (highly eutrophic)

- Median – lakes close to the Blue Ridge Ecoregion: 3
- Median – lakes close to the Coastal Plain Ecoregion: 8
- Range within the Piedmont Ecoregion: 3 - 8
- Best achievable improvement: if the lake is a 3 then it may improve to a 2, but if the lake is an 8 then it may improve to a 5.
- In the Piedmont Ecoregion, point sources are still the largest contributor of nutrients. Replacing all wastewater treatment plant collection systems and installing the best nutrient removal methods available could cause the biggest improvement in nutrient reductions.
- The impact of nutrient improvements will not be immediately realized. One would first see improvements in the tributaries before the improvements would be seen in the lakes.
- Even if all the human sources of nutrients were removed, the Piedmont lakes could never get to a 1 because of the natural nutrient sources.

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

### Designated Use, Primary Contact Recreation

The following are other variables that affect a waterbody's attainment of primary contact recreation uses:

- Pathogens and pathogen indicators
- Human health issue
- The source can be the same for both eutrophication and pathogen problems, but eutrophication does not cause an increase in pathogens. Examples of these similar sources include wastewater treatment plants and agriculture.
- Water clarity and visibility
- Both an aesthetic and safety issue
- Toxic algae from algal blooms
- Human health issue

### Designated Use, Secondary Contact Recreation

The following are other variables that affect a waterbody's attainment of secondary contact recreation uses:

- Aesthetics – the appearance of the waters
- Water clarity and visibility

- Both an aesthetic and safety issue
- Fish community structure
  - Many of the lakes in the Piedmont ecoregion are stocked with large mouth bass.
  - It is hard to observe the change in the fish community structure.  
Increases in nutrients would likely change the fish community structure.  
The fish community would likely change to more pollutant tolerant species, which are arguably less desirable in the long-run.
  - Additionally, fish biomass growth is not linear with increases in nutrients. After a certain level of nutrients, the fish biomass will not increase as rapidly.
- Toxic algae from algal blooms
  - Human health issue, but not as likely to cause problems.

**Other comments:**

- I don't think that the criteria should be based on bioavailable nutrients because the nutrients can transform in water.
- I do not consider macrophyte growth as a byproduct of eutrophication because macrophytes are located in shallow areas. In this region, macrophyte growth is a result of habitat, not nutrient availability.

- Many of the lakes in the Piedmont region are managed by power companies. These companies pump water from the bottom of the lake to run the generator and then release the water to the downstream portion. Since the water at the bottom of the lake is oxygen poor, the water released downstream is oxygen poor. This greatly effects aquatic life.
- Drinking water could have taste and odor problems as a result of eutrophication. This is because there is an increase in organics in the source waters. There are also the potential for problems with THM's and other disinfection byproducts.

## **C.8 Piedmont: Daniel Tufford**

**Expert Elicitation Discussion for the North Carolina Piedmont Ecoregion**

**Dr. Daniel Tufford**

**May 22, 2006**

**Summarized by: Melissa A. Kenney**

### **What are the mechanisms that lead to eutrophication?**

- A natural process of increasing primary productivity. To have increased productivity depends on:
  - Light
  - Temperature
  - Nutrient availability
  - Carbon availability
- The residence time allows the biological processes to flourish.
- The nutrients enter the lake through the tributaries; this is the main entry of nutrients into the reservoir.

### **Nutrient sources**

- Wastewater treatment plant
  - Municipal

- Industrial
- Local facilities
- Non-point sources
  - Agriculture
  - Urban runoff
- Precipitation
  - Unclear how significant of a source

### Eutrophication processes

- Increased nutrients lead to an increase in phytoplankton growth. This can lead to a number of effects such as:
  - Increase in toxic microorganisms
  - Increase in odor
  - Increase in turbidity
  - Decrease in oxygen levels during the algal decay process
  - Fish kills resulting from anoxic or hypoxic conditions
    - Fish are oxygen and temperature sensitive
- Additionally, all things equal, light and temperature are the largest regulator of the eutrophication status.
- The nutrient that is least available is the nutrient limiting phytoplankton growth.

- In general, phosphorous is the nutrient that is of highest concern because of its bioavailability.
  
- The eutrophication process is the same in the Piedmont ecoregion and the other ecoregions in the state, but the drivers of this process can be different in different ecoregions.
  - The Piedmont lakes are more turbid, which affects the light availability.
  - If the turbidity of the water is due to clay particles, then the phosphorous can bind to these particles reducing the phosphorous availability.
  - Temperature drives the phytoplankton assemblages.

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

**Designated Use, Primary Contact Recreation**

The following are other variables that affect a waterbody's attainment of primary contact recreation uses:

- Microbial contamination
  - Fecal coliform
  
- Metals

- Hydrocarbon
- Macrophytes
  - Makes it difficult to swim
- Dead fish in the water
- Turbidity
  - Affects the feel of the water and the water clarity
- Aesthetics
- Safety issues
- Water level
  - Don't want it too low

### Designated Use, Secondary Contact Recreation

The following are other variables that affect a waterbody's attainment of secondary contact recreation uses:

- Macrophytes
- No fish or few fish in the water
  - Want desirable fish species such as bass, brim, crappie, etc.
  - Fish biomass
- Large floating debris
- Boating etiquette

- Water level
  - Don't want it too low
- Contamination
  - Microbes
  - Hydrocarbons
  - Metals
- Aesthetics
- Dead fish
  - Can be an indicator of potential problems in the lake
- Development along the lake shoreline

**Other comments:**

- Lots of people like moderately eutrophic lakes because of the increase in secondary productivity that occurs as a result of this state. An increase in zooplankton, which is the main food source of many fish, leads to an increase in small fish species and, ultimately an increase in large fish species.
- There is a conflict between recreational users and fishermen.
  - Fisheries management would like eutrophic conditions because it creates desirable recreational fishing conditions.

- The regulatory agencies would like lakes managed to achieve a less eutrophic state.
- The primary function of many of these reservoirs is power generation, so many of them are managed by the utilities. As a result there is a perpetual tug-of-war pull between 3 different groups:
  - The lake is a water of the state so it is under the regulatory control of the state
  - The power company manages the lake
  - The 3<sup>rd</sup> party stakeholders use the lake

## **C.9 Southeastern Plains: Stephen Whalen**

Expert Elicitation Discussion for the North Carolina Southeastern Plains

Ecoregion

Dr. Stephen Whalen

March 2, 2006

Summarized by: Melissa A. Kenney

**What are the mechanisms that lead to eutrophication?**

- Nutrients enter the lake through point and nonpoint sources. The primary point sources in the Southeastern Plains are wastewater treatment plants and industrial sources. The major nonpoint sources are from agroecosystems and development. In addition to direct runoff into the lake, nutrients enter the lake through surface waters, groundwaters, and atmospheric deposition.
- After the nutrients enter the lake water, attached algae in shallow areas take them up. These include epilithic (attached to rocks), epipellic (on mud) and epiphytic algae(attached to plants).
- In the littoral zone , the nutrients also affect growth of submerged, floating leaved and emergent macrophytes.
- In deeper water, the phytoplankton become more important

- Next, as a lake ages or becomes more impacted by development, increased turbidity eventually decreases nutrients sequestered in phytoplankton.
- These effects can all be transferred up the ecosystem through higher trophic levels.

### Processes in Lakes

- Lake mixing affects shallow lakes because it stirs up the sediments on the bottom of the lake. When the sediments on the bottom are stirred up, nutrients are released into the water column.
- The release of the nutrients into the water column causes anoxic conditions, if extreme.
- Lakes that are very dendritic have a longer turnover time in certain areas of the lake.

### Nutrients in Lakes

- Historically, the best relationships are between total phosphorous and chlorophyll a. Although, time is the one caveat. Time scale and residence time is important because in the short-term, lakes can be either nitrogen or phosphorous limited. The availability of these nutrients is important to the lake systems. Nutrient concentrations and size of algal populations affect the turnover time for nutrients, another consideration.

- Lakes, however, are primarily phosphorous limited; therefore, phosphorous concentrations provide a lot of the necessary information.
- In North Carolina, the lakes are very turbid. Therefore, light is a big issue in determining algal population size.
- Lakes in this region are frequently highly colored. This naturally highly colored condition is from humics in dissolved organic matter. This coloration limits growth and productivity of phytoplankton by limiting light penetration.
- Many rivers have high nutrients and little chlorophyll a due to colored material. Hence nutrients are sometimes not the limiting factor. Light availability may be more important.
- In lakes, by the time autochthonous turbidity limits light, most of these lakes already have algal scums and standing concentrations of nutrients. In other cases, development leads to high input of silt and clay. Both circumstances cause shading of algae that allows high nutrient concentrations to persist.
- Turbidity and eutrophication to some extent go hand in hand, although there are lots of feedback loops. Therefore, you need to go case by case to determine if there is a difference.
- Both turbidity and high phytoplankton populations can lead to low dissolved oxygen. This occurs through abiotic or biotic processes. If it is abiotic (silt), then the source is anthropogenic, from construction activities that limit light

penetration. This limits oxygen production by phytoplankton and can contribute materials from the watershed that consume oxygen during decomposition. We have generally done a poor job of controlling sedimentation. If it is biotic, then the low dissolved oxygen is from excessive algae that not only produce oxygen from photosynthesis, but consume oxygen during death and decomposition. The source of this problem is generally anthropogenic (still-excessive nutrient input), but to a degree, both problems can be lessened through management.

### **Eutrophication Continuum**

Scale of 1 (highly oligotrophic) – 10 (highly eutrophic)

- Average = 7
- Range = 3 – 10
- Best achievable improvement: The best we could do in this area is a 3-4. There is too much anthropogenic activity to do better. Additionally, all the lakes are man-made so the watershed area is different, which changes the input-output exchanges. Morphometry is also different on a case by case basis. If a lake is dendritic, the dynamics of each arm may vary.

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

### Primary Contact Recreation

- Coliform bacteria -- people can get sick when exposed
- Pharmaceuticals and their byproducts – we don't know how they really effect people
- Algal scums-if not caused by human activity
  - Cyanobacteria are an undesirable species because they cause surface algal blooms in the photic zone. They are also an undesirable food source for zooplankton because it has low food quality.
- Submerged or merged aquatic vegetation
- Noxious algal blooms-again if not anthropogenic in origin. These can occur as a lake naturally ages
- Sediment type on the bottom of the lake
- Aesthetics – highly turbid conditions are undesirable

### Secondary Contact Recreation

- Weeds – undesirable for boating, but desirable for fishing
- Algal scums – undesirable for fishing when it wraps around the bait
- Heavy metals and PCBs – affect fishing

**Other comments:**

- There are some exceptions to my comments on designated use attainment. For example, Lake Mattamuskeet has a lot of weeds, but it provides habitat for ducks and enjoyment for duck hunters.
- Designated uses should be more specific because of competing uses and users' desires.

**How did you make your judgments?**

- Placed more stock in the dissolved inorganic nitrogen and total phosphorous values. However, these represent only what is left over after the phytoplankton have met their requirements. It gives some indication of the remaining potential to make phytomass and the ratio gives some indications to whether that phytomass will be heterocystous cyanobacteria.
- Looked at chlorophyll a, Secchi, and turbidity to figure out both trophic status and recreational use judgments.
- Used Secchi and turbidity to determine whether I thought a lake had a low light climate due to biotic or abiotic factors. This was used in my judgment of suitability for primary or secondary contact recreation.
- Paid little attention to surface dissolved oxygen measurements, unless they were horrendous.

- Put less stock in total nitrogen values than concentrations of other nutrients.

**Is there any data that would have been useful to make your judgments?**

- Midsummer hypolimnetic dissolved oxygen and temperature
- Percent saturation for oxygen, as the percent saturation will change with temperature and will put oxygen concentrations in the correct context.
- Lake size or maximum depth

## **C.10 Coastal Plain: Larry Cahoon**

**Expert Elicitation Discussion for the North Carolina Coastal Plain Ecoregion**

**Dr. Larry Cahoon**

**September 6, 2006**

**Summarized by: Melissa A. Kenney**

### **What are the mechanisms that lead to eutrophication?**

- Eutrophication can occur from both natural and cultural processes.

#### **Natural eutrophication**

- Soil and organic matter are eroded. This matter and the attached nutrients are deposited into waterbodies.
- This process leads to a natural succession of lakes where, over time, the lakes become shallower from deposited sediment. There is a transition from microphytes to macrophytes along the bottom. Once the rooted plants take hold, then primary productivity is not light limited; it is nutrient limited.
- The process of eutrophication is one in which increased nutrients in the waterbody cause an increase in primary productivity. The increase in algal growth can lead to an increase in algae blooms. Additionally, there is an increase in vegetation loading (macrophytes and phytoplankton). Although

phytoplankton do not have levels high enough to cause fish kills, the increase in vegetation loading, in general, can lead to fish kills.

- Finally, as the process progresses the dissolved oxygen levels decrease, leading to fish kills when the dissolved oxygen is below 90% saturation. Fish kills can occur within a matter of hours when dissolved oxygen levels are sufficiently low. Another thing to mention is that there is a time lag as a result of in lake processes.

### Cultural eutrophication

- The process of eutrophication is the same whether it is natural or cultural; however, the sources and time scale vary.
- Cultural eutrophication is eutrophication that has been accelerated due to anthropogenic causes. Cultural eutrophication occurs primarily from accelerated sedimentation and nutrient loading from indirect sources, such as agriculture and residential areas, or direct sources, such as point sources. Cultural eutrophication can occur because of changes in land use, hydrology, and the residence time of the waterbody.
- More specifically, humans have added to the process through changing hydrology, dredging, withdrawing/adding water and accelerating run-off.

- The main management scheme for cultural eutrophication is dredging and/or plant removal.
- Eutrophication is not a one-way process, it can be reversed as a result of extreme and deliberate efforts.

## Sources

- Water from storm runoff travels fast into receiving waters.
  - Facilitated drainage is correlated with impervious cover (sometimes)
  - Faster drainage changes the hydrology.
    - Clay tile drains in agricultural fields
- Sedimentation
- Nutrients
- Organic loading
  - Metals and coliform – not necessarily eutrophication but they covary with eutrophication variables
- Can also have problems as a result of the airshed.

## Non-natural Lakes / Reservoirs

- Reservoirs tend to be deeper. They are designed for flood control or recreation.  
The coastal plain reservoirs also tend to be smaller than the reservoirs in the Piedmont.

- These lakes were created by damming a natural stream and/or excavating the area.

## Natural Lakes

- Mixing regime is not as common in North Carolina because the lakes are shallow.
  - Most are not dimictic; they are polymictic or uniform throughout the entire water column.
- Coastal lakes are mostly natural. Many are elliptical in shape.
  - This shape most likely result from the last glacial period where they were wind ablation basins.
  - These lakes are vulnerable to eutrophication.
    - If macrophytes get rooted, they can tap bottom sediment nutrients, although there are not a lot of bottom sediment nutrients in the natural lakes.
- There are a lot of local differences in eutrophication.

## Eutrophication Continuum

Scale of 1 (highly oligotrophic) – 10 (highly eutrophic)

- Median: 8 (non-natural lakes) and 2 --3 (natural lakes)

- Range: 7 – 10 (non-natural lakes) and 1 – 4 (natural lakes)
- Best achievable improvement: For non-natural lakes, the nutrient loads need to be managed by trapping them in the tributaries. It is difficult to remove nutrients in the sediment and would take quite a bit of time, but if this occurred then the best improvement would be a change to a 5 – 7. For natural lakes, improvements in storm water management and sewage or septic tanks could improve the condition to a 1 – 2. Again, it would take quite a bit of time to realize this improvement. Finally, a waterbody can have localized problems where it will be a 9 or 10. The most improvement would be realized in these parts; they could be improved to a 4 or 5.

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

**Designated Use, Primary Contact Recreation**

The following are other variables that affect a waterbody's attainment of primary contact recreation uses for both non-natural and natural lakes:

- Fecal coliform and pathogens
  - This is a conservative measure; it does not protect against all health problems.

- Toxic algae, blue-green algae, or cyanobacteria
- Weeds and macrophytes
- Sedimentation or muddy water
- Slimy water
- Aesthetics
  - Water clarity, turbidity, and sediment
  - Macrophytes
  - Algal scums (somewhat indicated by chlorophyll *a*)
  - Water color
    - The natural lakes may have black water; this is indicative of high water quality in these lakes. Black water a natural occurrence that causes the water to have a low pH and low levels of pathogens.
    - Green water is indicative of high algae and is not good.
  - Odor
    - Anything detectable is not good.

### Designated Use, Secondary Contact Recreation

The following are other variables that affect a waterbody's attainment of secondary contact recreation uses for both non-natural and natural lakes:

- Fecal coliform and pathogens

- This is a conservative measure; it does not protect against all health problems.
- Toxic algae, blue-green algae, or cyanobacteria
- Weeds and macrophytes
- Sedimentation or muddy water
- Slimy water
- Aesthetics
  - Water clarity, turbidity, and sediment
  - Macrophytes
  - Algal scums (somewhat indicated by chlorophyll *a*)
  - Water color
    - The natural lakes may have black water; this is indicative of high water quality in these lakes. Black water is a natural occurrence that causes the water to have a low pH and low levels of pathogens.
    - Green water is indicative of high algae and is not good.
  - Odor
    - Anything detectable is not good.
- Fish consumption
  - Natural parasites (slight risk)

- Natural toxins (little risk in freshwater)
- Bioaccumulated metals (such as mercury), PCBs, and pesticides
  - These can be airborne so there may be no visual indicator.
- Sport fishing
  - Anything is ok if it is catch and release

### **How did you make your judgments?**

#### **Assessments for eutrophication category:**

- Focused on chlorophyll *a* first
  - Expected the chlorophyll *a* levels to be higher in the reservoirs
  - Below is the approximate scale used to rank the chlorophyll *a* levels for reservoirs
    - < 10 µg/L is low
    - 10 – 30 µg/L is moderate
    - > 30 µg/L is high
- Next considered the ratio of total nitrogen to total phosphorous
  - A ratio of <5:1 favors bacteria to phytoplankton growth
  - If the absolute value numbers are high, then this is factored into the assessment

- Below is the approximate scale used to rank total phosphorous
  - < 0.05 mg/L is low
  - 0.05 – 0.1 is moderate
  - > 0.1 is high
- Looked at dissolved oxygen
  - It was unusual to find a low value (below 90% saturation or 5 mg/L)
  - If the value was really high (> 10 mg/L), then this was a signal of eutrophic conditions because the oxygen is being super saturated near the upper layer of water.
  - If the value wasn't high or low, then dissolved oxygen didn't say much.
- Looked at Secchi and turbidity together
  - These values should correlate, but the relationship isn't perfect
  - If there were very high turbidity levels, then it was indicative of potential bacterial presence

#### Assessments for primary contact recreation:

- Used variables to indirectly assess bacteria since this is important for primary contact recreation
  - chlorophyll *a*
    - downplayed in non-natural lakes vs. natural lakes

- ratio of total nitrogen to total phosphorous
- turbidity
- When the values didn't vary together in the expected way, it was more difficult to assess risk

Assessments for secondary contact recreation:

- Focused primarily on the fishability of the water
- Several variables were indicative of potential problems
  - High turbidity levels
  - Low dissolved oxygen
  - Super high chlorophyll *a* levels
- Unless there was a clear signal or message in the data, the judgments tended to be spread out to account for the uncertainty in making the assessment.

**Other comments:**

- Perception indicators can be misleading about the potential problems of the waterbody.

**Is there any data that would have been useful to make your judgments?**

- Macrophyte biomass
- Actual coliform or other direct fecal contamination measures

## **C.11 Coastal Plain: Robert Christian**

**Expert Elicitation Discussion for the North Carolina Coastal Plain Ecoregion**

**Dr. Robert Christian**

**August 24, 2006**

**Summarized by: Melissa A. Kenney**

**What are the mechanisms that lead to eutrophication?**

### **Natural Lakes**

- The natural lakes do not have significant riverine systems that enter the lake.
  - As a result, the watersheds are fairly localized.
- The major source contributions are from land use changes. These include:
  - Silviculture: runoff of organic soils
  - Agriculture: nutrient runoff
  - Industry: locally important, but not much of an issue for these lakes
  - Waterfowl: nutrient source since this is a major wintering location for birds
  - Suburbanization: runoff
  - Septic tanks: nutrients from poorly maintained tanks
  - Wastewater Treatment Plants: nutrients from overflow

- Lawns: nutrient runoff
- The land around the natural lakes is mainly protected, so land use changes are not a huge issue currently.
- Eutrophication is the result of increased primary production. This increases the potential for algal blooms, decreases submerged aquatic vegetation, and can cause changes in pH.
- There can also be increases in secondary production. Though some increase is good, too much can cause undesirable results.
- Water clarity can change rapidly in these lakes because the lakes have a long fetch and are shallow.
- The bottom sediment is organic rich and can quickly incorporate into the water if there is mixing.
- Dissolved oxygen may not be a major concern, except locally. These lakes are very shallow so there should be a good bit of mixing.
- Some of these lakes are black water lakes. The water becomes highly colored when the wind picks up.
- These lakes are much clearer than those in the Piedmont.

### Non-natural Lakes / Reservoirs

- The purpose of the lake determines the likely condition of the lake.

- These lakes have the potential to export water.
- There is greater flow through of water (volume). This occurs because there are more directions for the water to go.
- If the reservoirs are deeper than the Carolina Bays, then there may be hypoxia issues and stratification.
- The land use problems are more intense. Nutrients result from:
  - Confined Animal Feeding Operations CAFOs
  - Agriculture
  - Development
  - Silviculture
- The eutrophication process is the same for both natural and non-natural lakes.

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

**Designated Use, Primary Contact Recreation**

The following are other variables that affect a waterbody's attainment of primary contact recreation uses for both non-natural and natural lakes:

- Pathogens
  - Human or waterfowl

- Low pH
- Presence of wildlife or fowl
  - can deter or restrict lake use
- Aesthetics
  - muddy bottoms
- Eutrophication problems

### Designated Use, Secondary Contact Recreation

The following are other variables that affect a waterbody's attainment of secondary contact recreation uses for both non-natural and natural lakes:

- Waterfowl
  - restricts use of boats
- Access issues to waterbody
- Pathogens
  - shellfish consumption
- Heavy metals
  - Fish contamination and consumption
- Low pH
  - Fewer fish

- May not be an impairment since it could be a reference condition for black water lakes
- Aesthetics

### **How did you make your judgments?**

#### Eutrophication

- Focuses on nutrients (TIN and TP) and Chlorophyll a
- Put less emphasis on turbidity and dissolved oxygen (unless very low)
- Lumped Secchi and turbidity when making assessments

#### Primary and Secondary Contact Recreation

- Dissolved oxygen had a larger role because of organic matter contamination.
- Similar value structure for the variables as the assessment for eutrophication.

## **C.12 Coastal Plain: Hank McKellar**

**Expert Elicitation Discussion for the North Carolina Coastal Plain Ecoregion**

**Dr. Hank McKellar**

**July 12, 2006**

**Summarized by: Melissa A. Kenney**

### **What are the mechanisms that lead to eutrophication?**

- The major source of nutrients in the Coastal Plain Ecoregion is nonpoint source pollution from urbanization. The increase in impervious surfaces causes an increase in runoff, which transports nutrients.
- There are other additional nonpoint source nutrient sources. Agriculture can contribute nutrient from fertilizer use on crops or manure runoff from livestock. There can also be nutrient sources from atmospheric deposition, particularly N-laden deposition. Finally, poor working septic tanks can leak nutrients.
- Point sources can also contribute nutrients. In the Coastal Plain, these sources can be municipal wastewater treatment plants and industrial discharge.
- Nutrient concentrations tend to be higher in the Coastal Plain since this region is the furthest downstream location. These systems, since they are located further

downstream than those in the other Ecoregions, may be naturally adapted to higher levels of nutrients.

### Non-natural Lakes / Reservoirs

- Nutrients typically enter reservoirs mainly through a major tributary at the upper end of the reservoir.
- Nutrient levels are higher at the upper end of the reservoir and decrease in the lower reaches due to uptake and sedimentation during transit from the upper end of the reservoir. This leads to important spatial considerations for classification of the eutrophication status.
- Turbidity also tends to be higher in the upper ends, due to inflowing suspended sediments. This turbidity can inhibit algal growth due to light limitation. As the suspended sediments sink out of the water, turbidity decreases and, if sufficient nutrient levels remain, there can be a spike in the algal growth, typically in the upper half of the lake.
- Eutrophication occurs when high levels of nutrients cause excessive algal growth. While algal peaks typically occur in the upper half of the lake, the algae are transported down to the lower reaches where they die, sink, and consume oxygen in the decay process. This can cause anoxic or hypoxic conditions.

- Another algal growth factor is the residence time of the waterbody; these reservoirs have relatively short residence time which can decrease the potential for excessive algal blooms within the lake
- Some nutrient enrichment is not necessarily negative; in fact, higher productivity can be good since there is an increase in biomass and productivity.
- Excessive algal growth can become troublesome, however, when the high algal growth rate causes a change in the ecosystem dynamics. Higher eutrophic conditions can cause an increase in less desirable algal species, such as blue-green algae. Also, when there is higher levels of eutrophication there can be a shift to more pollution tolerant species, which are less desirable than the naturally occurring organisms. Finally, when algal growth becomes excessive, it can contribute to lower oxygen levels, which can affect the habitat of higher trophic level organisms.
- Low oxygen levels in the lower depths of the reservoir are also a natural process, but the extent and duration of hypoxic conditions can be exacerbated by the effects of eutrophication.

## Natural Lakes

- Natural lakes are less affected by point source pollution. Instead, they are more affected by nonpoint source pollution sources, because they often have smaller,

more localized watersheds. Therefore, there are less eutrophication spatial and temporal effects.

- Watershed drainage In the Coastal Plain, often produces blackwater streams caused by humic substances (tannic and fulvic acids) leached from decaying vegetation. When blackwater streams feed the natural lakes, the lake can also be stained with humic substance.
- These systems can have lower nutrients because the nutrients have been absorbed as the source water drains through decaying vegetation and soils.

Therefore these lakes are naturally more oligotrophic.

- The amount of tannic and fulvic acid in the lake, is effected both by the size of the lake and the lake's river source.
  - The stained waters cause a light limitation that can inhibit algal growth.
  - Because of this natural condition, these systems may be more sensitive to nutrient loading. There could be higher instances of attached algal growth from smaller amounts of nutrients than non-natural systems.
- Even though these lakes are less deep than the non-natural systems, their residence time is longer. This means that these lakes have less flushing than the reservoirs.

## **Eutrophication Continuum**

Scale of 1 (highly oligotrophic) – 10 (highly eutrophic)

- Average: 7 (non-natural lakes) and 5 (natural lakes)
- Range: 5 -- 8 (non-natural lakes) and 4 -- 7 (natural lakes)
- Best achievable improvement: it is difficult to improve the trophic status of lakes in these regions because of all the different pollution sources; this makes management even more difficult. It is unrealistic to convert these waterbodies to an oligotrophic state, but it is realistic to improve them to a mesotrophic state.

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

**Designated Use, Primary Contact Recreation**

The following are other variables that affect a waterbody's attainment of primary contact recreation uses for both non-natural and natural lakes:

- Fecal coliform and other microbial pathogens
  - Can be correlated with eutrophication because higher runoff can be associated with nutrient and microbial contamination
- Aesthetics
  - Toxic algae

- Algal blooms
- Water clarity (from sediment or algae)
- Sedimentation / turbidity

### Designated Use, Secondary Contact Recreation

The following are other variables that affect a waterbody's attainment of secondary contact recreation uses for both non-natural and natural lakes:

- Fecal coliform and other microbial pathogens
  - Can be correlated with eutrophication because higher runoff can be associated with nutrient and microbial contamination
  - Smaller problem for secondary contact recreation users
- Aesthetics
  - Toxic algae
  - Algal blooms
  - Water clarity (from sediment or algae)
- Sedimentation / turbidity
- Consumption of fish from waterbody
  - Toxicants such as metals can cause human health problems if consumed

- Fish health – higher levels of pollution can cause lesions or morbidity problems in fish
- Fish habitat

### **How did you make your judgments?**

- Emphasized total phosphorous and chlorophyll *a*
  - Also considered total nitrogen and total inorganic phosphorous, but these weren't considered as important
  - Chlorophyll *a* was ranked using the scale below
    - < 10 – 15 µg/L is very low levels
    - 20 – 30 µg/L is moderate levels
    - > 40 µg/L is high levels
    - If the chlorophyll *a* are high than it can effect the primary contact recreational uses, but the chlorophyll *a* could stimulate secondary contact recreation. For chlorophyll *a* levels of 20 – 30 µg/L is good for fish productivity and temporary spikes in the 40s are not necessarily bad.
- Emphasized Secchi depth more than turbidity (NTU)
  - Turbidity is not necessarily eutrophication related

- If total phosphorous and chlorophyll *a* were high and turbidity was low, then it was considered more eutrophic
- If Secchi was < 1 m than it was considered not conducive to primary recreation; if t was < 0.5 m than it was considered to have detrimental effects to the secondary contact recreational uses, particularly fishing and aesthetics.
- Fecal coliform levels are correlated with the Secchi and turbidity levels; high coliform levels are associated with high turbidity levels. This can affect primary contact recreational uses.

## **C.13 Coastal Plain: Don Stanley**

**Expert Elicitation Discussion for the North Carolina Coastal Plain Ecoregion**

**Dr. Don Stanley**

**March 31, 2006**

**Summarized by: Melissa A. Kenney**

### **What are the mechanisms that lead to eutrophication?**

- The watersheds vary in size.
- There are natural and human-related eutrophication sources. The largest source of nutrients into the lakes is human-related sources. Of the human-related sources, there are point source and nonpoint source pollutant sources.

### **Nutrient Sources**

- The main nutrient contributors are from non-point sources. These sources include:
  - Agriculture
    - Fertilizer
    - Animal operations (non-Confined Animal Feeding Operations (CAFOs))
  - Urban runoff

- Impervious surfaces
  - Stormwater runoff
- Atmospheric deposition
- The point sources in the coastal plain ecoregion are:
  - Industrial sources
  - Municipal waste water treatment plants
  - Confined animal feeding operations

### Non-natural Lakes / Reservoirs

- The nutrients enter a body of water. If they enter a stream, then there are lots of in-stream processes. Unlike what some people think, streams do not act like a pipeline that directly transport materials from point A to B. Therefore, the amount of nitrogen and phosphorous that enter a lake is different than the amount that is coming from terrestrial systems. This is because of loss processes such as denitrification for nitrogen and sedimentation for phosphorous.
- Once the nutrients enter a lake then the nutrients can accumulate and lead to eutrophication. Eutrophication occurs when an increase in nutrients increases plant growth leading to an increase in secondary productivity (zooplankton) and finally increased productivity at the higher trophic levels.

- If the eutrophication process progresses, then there can be a chain of negative problems. If nutrients levels are extremely high then it can lead to excessive algal growth, which can lead to problems such as hypoxia and fish kills.

## Natural Lakes

- The natural lakes in the Coastal Plain are called the Carolina Bay Lakes.
- There are both similarities and differences between these natural lakes and the non-natural lakes that are located in the same ecoregion.
- The natural lakes have smaller drainage basins than non-natural lakes.
- There is not much of a difference between natural and non-natural lakes in terms of land use. Although, some natural lakes might be located in protected areas.
- The eutrophication sources for both natural and non-natural lakes are about the same.
- The eutrophication response in the bay lakes may be different than the average reservoir.
- The Carolina Bays are relatively shallow lakes.
- They can also be darkly stained from naturally high amount of humic material that enters the waterbodies. These lakes also may have lower pH levels from this humic material. The lakes can range in color from clear to tea colored.

- The biology might be different in these lakes, but it's unclear how they may be different.
- The eutrophication problems are likely the same as in the non-natural lakes. There may be, however, some differences in the manifestation of the problems for the stained waters because of reduced light availability.

### **Eutrophication Continuum**

Scale of 1 (highly oligotrophic) – 10 (highly eutrophic)

- Average: 5 (non-natural lakes) and 5 (natural lakes)
- Range: 4 – 9 (non-natural lakes) and 4 -- 7 (natural lakes)
- Best achievable improvement: the best both the non-natural and natural lakes could achieve is a 4. These lakes are not oligotrophic; anything less than a 4 would be unnatural for these systems.

**What other variables (non-eutrophication) affect a waterbody's attainment of designated use?**

**Designated Use, Primary Contact Recreation**

The following are other variables that affect a waterbody's attainment of primary contact recreation uses for both non-natural and natural lakes:

- Toxics

- Pesticides
  - Industrial discharge
- Transmissible disease organisms
  - Water-borne human diseases or pathogens
- Potential animals
  - Snakes or other potentially dangerous animals
- Aesthetics
  - Odor
  - Taste
  - Visible algal scums
- Dead animals or fish
- Toxic algae or other biotoxins
- Sedimentation
  - Suspended sediment

### Designated Use, Secondary Contact Recreation

The following are other variables that affect a waterbody's attainment of secondary contact recreation uses for both non-natural and natural lakes:

- Aesthetics
- Rooted aquatic plants

- Obstructions in the water
  - Floating logs, tree stumps, etc.
  - Some of these obstructions are important for fish habitat but are undesirable for maneuvering boats
  
- Climate
  - Wave height, etc.
  
- Bioaccumulation / biomagnification of toxins
  - Cannot eat the fish
  
- Type of fish present
  - Species of fish
    - The appropriate fish species may be different in the natural vs. non-natural lakes. This may lead to different management of the fish stock.

**Other comments:**

- There is a conflict between the two designated uses. Primary contact recreational users, such as swimmers, want a sandy bottom and little shoreline vegetation. Fishermen want muddy bottoms and vegetation along the shoreline.
  
- In terms of the general trophic status of a lake, swimmers want clear, clean lakes and fishermen would like more eutrophic waters.
  
- User's perception of water quality is largely based on the aesthetics of the lake.

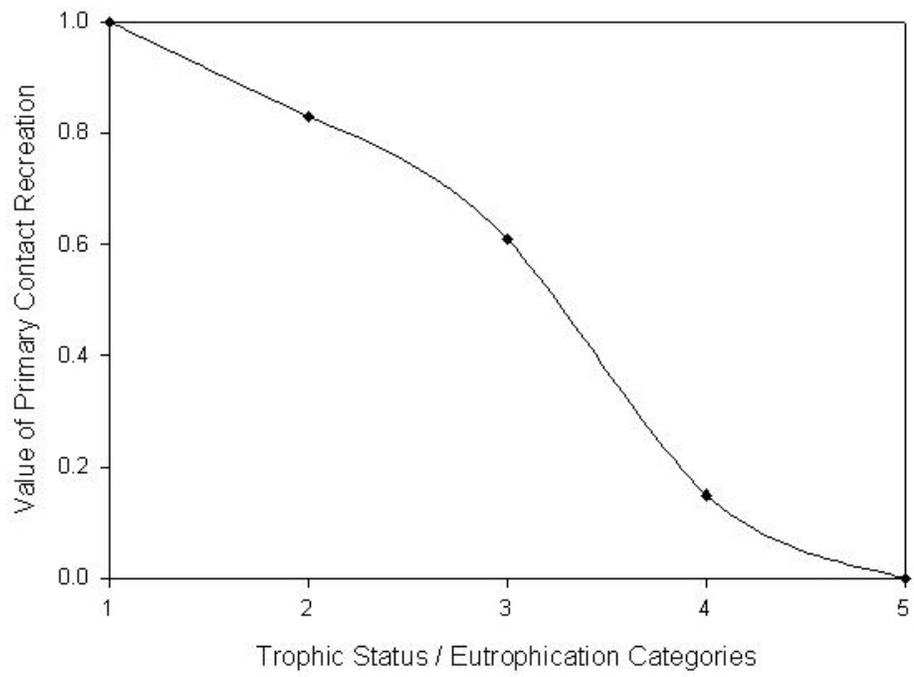
- The Carolina Bays are not excessively eutrophic; outliers for these systems are less extreme than in the non-natural systems.

## **Appendix D: Value Assessment for North Carolina Nutrient Criteria**

### ***D.1 Marion E. Deerhake's Value Assessment***

#### **D.1.1 Primary Contact Recreation**

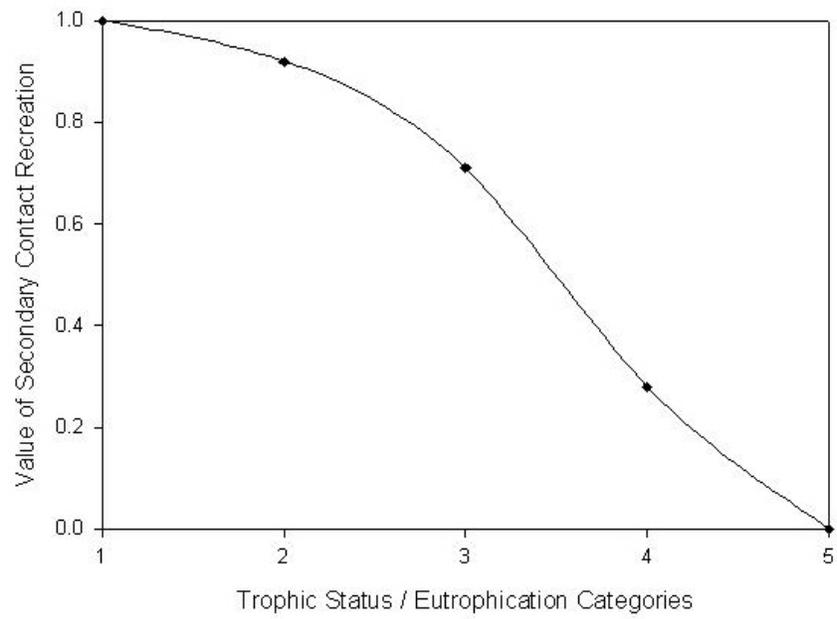
Figure 19 describes the values that Ms. Deerhake relayed during the interview for primary contact recreation for the given trophic status categories. As this function indicates, Ms. Deerhake thought that for primary contact recreation a trophic status 3 was closer in value to the ideal trophic category, 1, than the worst trophic category 5. Additionally, Ms. Deerhake thought that a category 2 was closer to a 1 than a 3 and that a category 4 was closer in value to a 5 than a 3. This was confirmed through her explanation that there was a greater loss in value for primary contact recreation below a category 3. After more specifically defining the values, 1 was the best at a value of 1, 2 was 0.83, 3 was 0.61, 4 was 0.15, and 5 was the worst level for a value of 0.



**Figure 19: Value of Primary Contact Recreation for the Eutrophication Status Categories Marion E. Deerhake**

### **D.1.2 Secondary Contact Recreation**

Figure 20 describes the values that Ms. Deerhake relayed during the interview for secondary contact recreation for the given trophic status / eutrophication categories. As this function indicates, Ms. Deerhake thought that, in comparison to primary contact recreation, that secondary contact recreation retains more of its value for trophic status / eutrophication categories 2, 3, and 4. For secondary contact recreation, Ms. Deerhake thought that the value of a category 2 was 50% more desirable than the value she defined for a category 2 for primary contact recreation. Similarly for a category 3, she thought that the value of secondary contact recreation was 75% more desirable, and for a category 4 the value of secondary contact recreation was 85% more desirable. Therefore the values are the same: 1 was the best at a value of 1, 2 was 0.92, 3 was 0.71, 4 was 0.28, and 5 was the worst level for a value of 0.



**Figure 20: Value of Secondary Contact Recreation for the Eutrophication Status Categories Marion E. Deerhake**

### D.1.3 Cost

Ms. Deerhake said that her value function for cost is linear because there is the same loss of value going from 0 to 2.5 million as from 2.5 to 5 million, making 2.5 million the midpoint value. More specifically defining the values, 0 cost was the best at a value of 1, 1.25 million was .75, 2.5 million was .5, 3.75 million was 0.25, and 5 was the worst level for a value of 0.

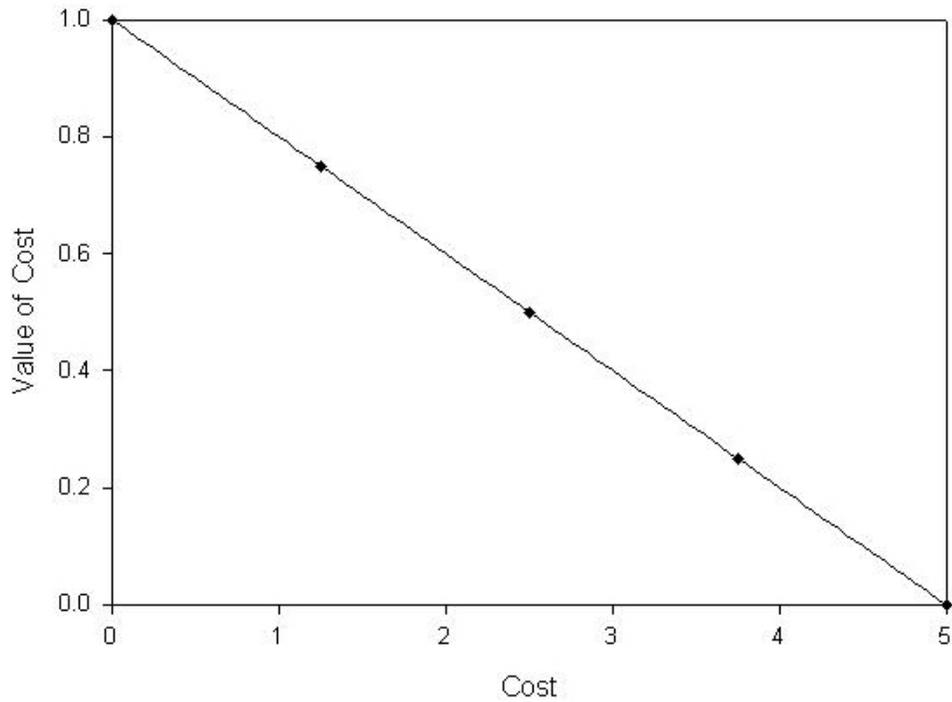


Figure 21: Value of Cost Marion E. Deerhake

#### D.1.4 Trade-offs between Attributes

The weights were calculated by determining indifference points between two of the attributes, 1) primary contact recreation and cost, and 2) secondary contact recreation and cost. For primary contact recreation and cost and for secondary contact recreation and cost, the assessed indifference point is 5 million dollars and a category 3. The weights were calculated using these indifference points and the value function. Given Ms. Deerhake's current rankings and the weights calculated from the indifference points, her rankings and weights are consistent.

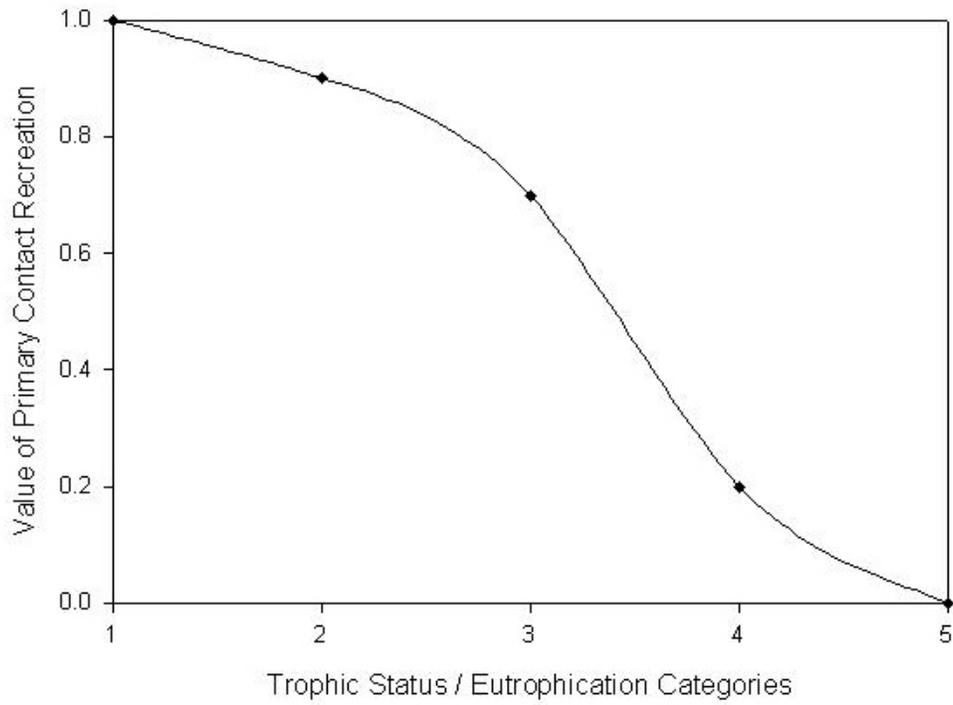
**Table 20: Marion E. Deerhake Trade-offs between Attributes**

	Ranking	Weights
Primary Contact Recreation	1	0.40
Secondary Contact Recreation	2	0.35
Cost	3	0.25

## ***D.2 David H. Moreau's Value Assessment***

### **D.2.1 Primary Contact Recreation**

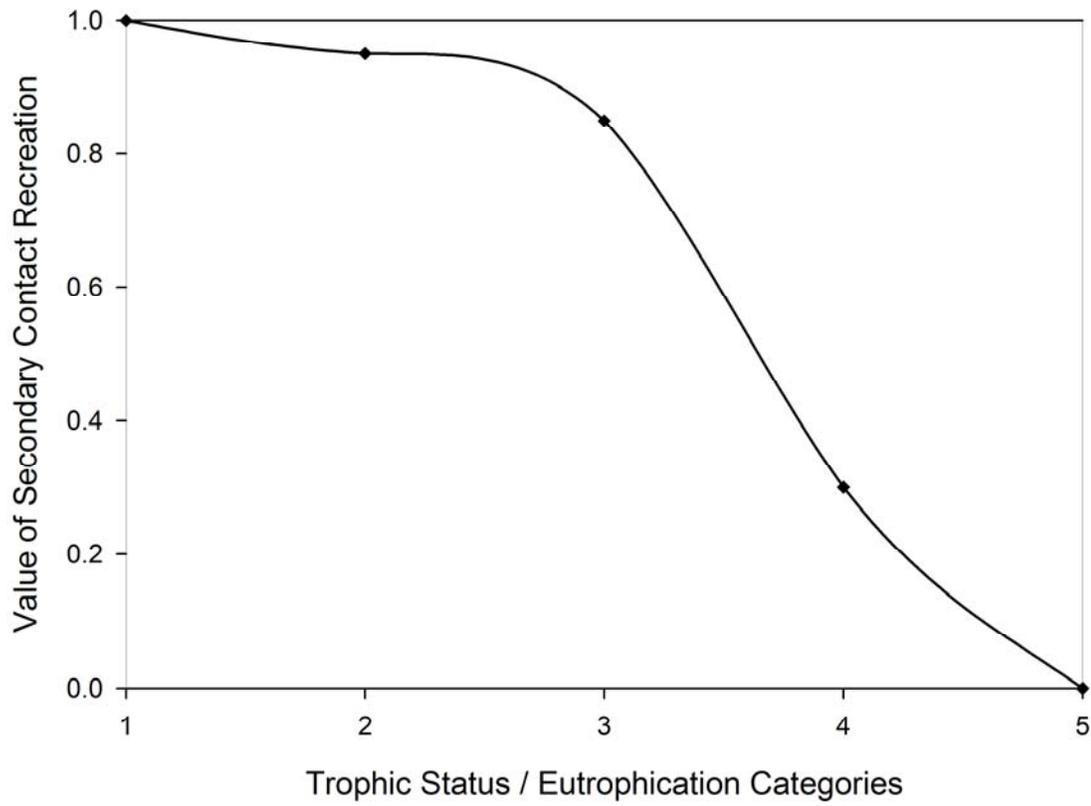
Figure 22 describes the values that Dr. Moreau relayed during the interview for primary contact recreation for the given trophic status categories. As this function indicates, Dr. Moreau thought that for primary contact recreation a trophic status 3 was closer in value to the ideal trophic category, 1, than the worst trophic category 5. Additionally, Dr. Moreau thought that a category 2 was closer to a 1 than a 3 and that a category 4 was closer in value to a 5 than a 3. This was confirmed through his explanation that there was not a large loss in value for primary contact recreation until the category dropped below a 3, with a category 3 being 70% of the value of the best and a category 4 being only 20% of the value of the best. After more specifically defining the values, 1 was the best at a value of 1, 2 was 0.9, 3 was 0.7, 4 was 0.2, and 5 was the worst level for a value of 0.



**Figure 22: Value of Primary Contact Recreation for the Eutrophication Status Categories David H. Moreau**

### **D.2.2 Secondary Contact Recreation**

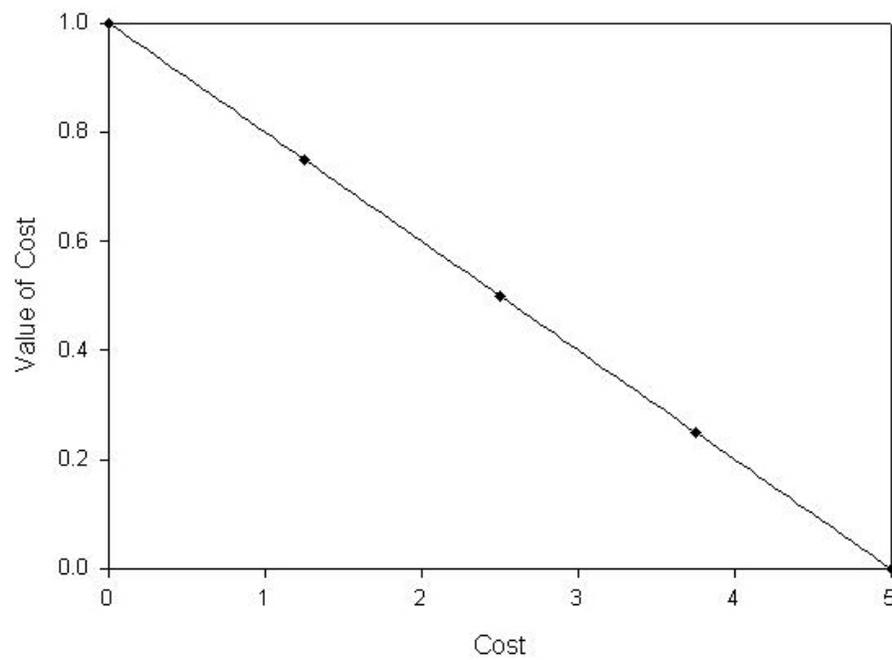
Figure 23 describes the values that Dr. Moreau relayed during the interview for secondary contact recreation for the given trophic status / eutrophication categories. As this function indicates, Dr. Moreau thought that, in comparison to primary contact recreation, the value would be slightly higher for categories 2 and 3, but would be lower for category 4. Dr. Moreau said that there is not a significant loss in value for secondary contact recreation until the trophic status is below a category 3. After more specifically defining the values, 1 was the best at a value of 1, 2 was 0.95, 3 was 0.85, 4 was 0.3, and 5 was the worst level for a value of 0. (Note: The green line is a smoothing line.)



**Figure 23: Value of Secondary Contact Recreation for the Eutrophication Status Categories David H. Moreau**

### D.2.3 Cost

Dr. Moreau said that his value function for cost is linear because there is the same loss of value going from 0 to 2.5 million as from 2.5 to 5 million, making 2.5 million the midpoint value. More specifically defining the values, 0 cost was the best at a value of 1, 1.25 million was .75, 2.5 million was .5, 3.75 million was 0.25, and 5 was the worst level for a value of 0.



**Figure 24: Value of Cost David H. Moreau**

#### **D.2.4 Trade-offs between Attributes**

The weights were calculated by determining indifference points between two of the attributes, 1) primary contact recreation and cost, and 2) secondary contact recreation and cost. For primary contact recreation and cost, the assessed indifference point is 5 million dollars and a category 2.5. For secondary contact recreation and cost, the assessed indifference point is 5 million dollars and a category 3. The weights were calculated using these indifference points and the value function. Given Dr. Moreau's current rankings and the weights calculated from the indifference points, there is an obvious inconsistency between the weights and the rankings; even though secondary contact recreation is ranked the highest, it only has the second highest weight (to be consistent it should have the highest weight).

Dr. Moreau stated that because he believed that primary contact recreation was a more sensitive use and therefore he may be more willing to spend money to restore secondary contact recreational uses since it would impact more recreational users and wouldn't cost as much money to restore. Therefore, he ranked secondary contact recreation first, then primary contact recreation, and finally cost. Though there was an inconsistency between his rankings and weights, with this explanation, the inconsistency is minor.

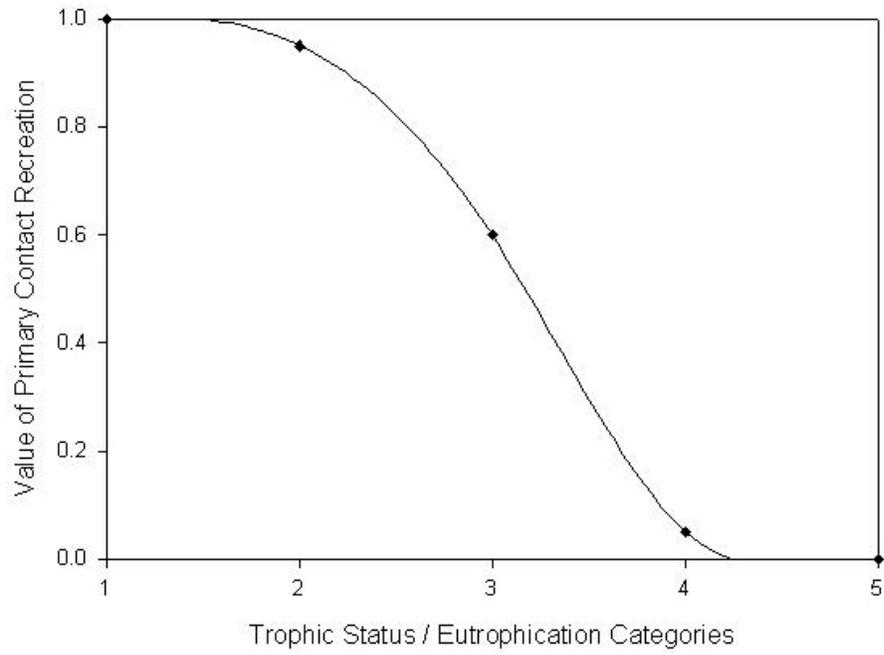
**Table 21: David H. Moreau's Trade-offs between Attributes**

	Ranking	Weights
Primary Contact Recreation	2	.36
Secondary Contact Recreation	1	.34
Cost	3	.3

## ***D.3 Charles H. Peterson's Value Assessment***

### **D.3.1 Primary Contact Recreation**

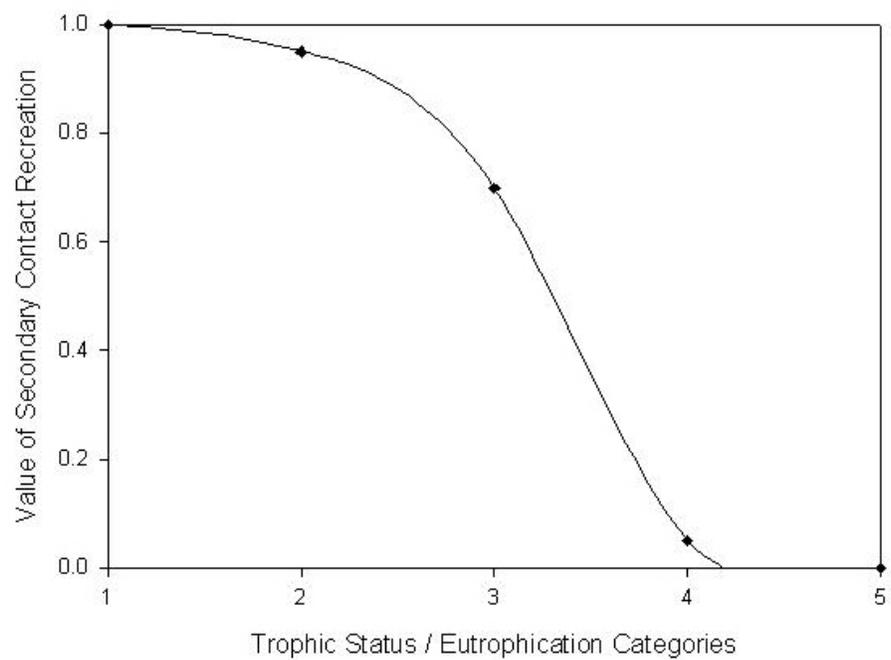
Figure 25 describes the values that Dr. Peterson relayed during the interview for primary contact recreation for the given trophic status categories. As this function indicates, Dr. Peterson thought that for primary contact recreation a trophic status 3 was closer in value to the ideal trophic category, 1, than the worst trophic category 5. Additionally, Dr. Peterson thought that a category 2 was closer to a 1 than a 3 and that a category 4 was closer in value to a 5 than a 3. This was confirmed through his explanation that there was not a large loss in value for primary contact recreation until the category dropped below a 2, with a category 3 being 60% of the value of the best and a category 4 being only 5% of the value of the best. Dr. Peterson directly provided the values where: 1 was the best at a value of 1, 2 was 0.95, 3 was 0.6, 4 was 0.05, and 5 was the worst level for a value of 0.



**Figure 25: Value of Primary Contact Rereation for the Eutrophication Status Categories Charles H. Peterson**

### **D.3.2 Secondary Contact Recreation**

Figure 26 describes the values that Dr. Peterson relayed during the interview for secondary contact recreation for the given trophic status / eutrophication categories. As this function indicates, Dr. Peterson thought that, in comparison to primary contact recreation, the values were the same except for category 3. For category 3, since Dr. Peterson thought that secondary contact recreation is a less sensitive risk, he determined that the value was 70% of the best value. As the value function indicates, Dr. Peterson said that there is not a significant loss in value for secondary contact recreation until the trophic status drops below a category 3. Dr. Peterson directly provided the values for the function where: 1 was the best at a value of 1, 2 was 0.95, 3 was 0.7, 4 was 0.05, and 5 was the worst level for a value of 0.



**Figure 26: Value of Secondary Contact Recreation for the Eutrophication Status Categories Charles H. Peterson**

### D.3.3 Cost

Dr. Peterson said that his value function for cost is linear because there is the same loss of value going from 0 to 2.5 million as from 2.5 to 5 million, making 2.5 million the midpoint value. More specifically defining the values, 0 cost was the best at a value of 1, 1.25 million was .75, 2.5 million was .5, 3.75 million was 0.25, and 5 was the worst level for a value of 0.

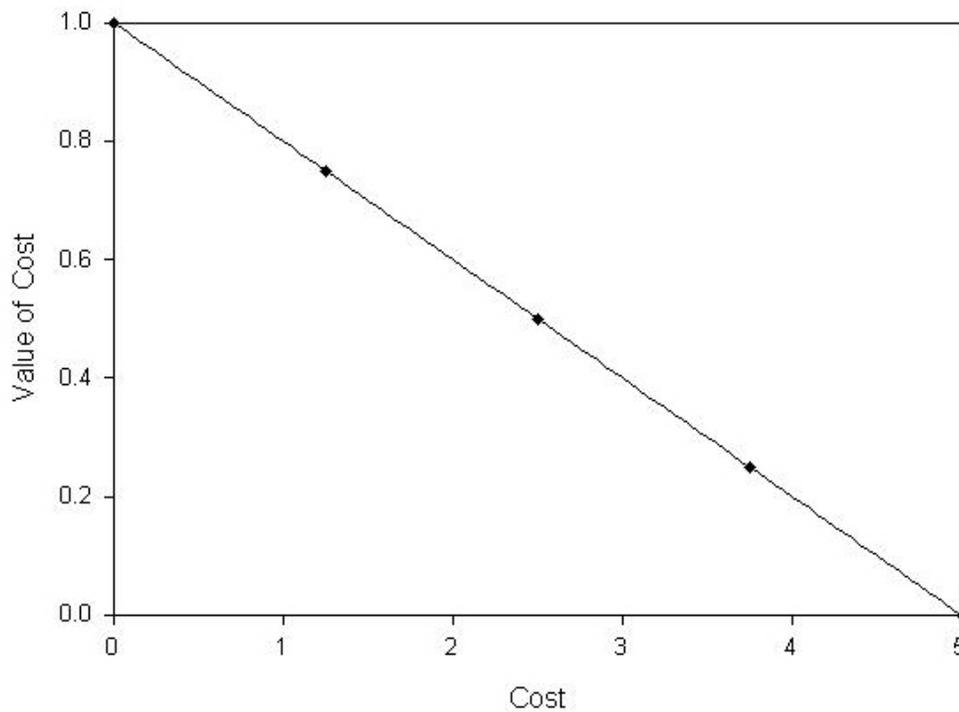


Figure 27: Value of Cost Charles H. Peterson

### D.3.4 Trade-offs between Attributes

The weights were calculated by determining indifference points between two of the attributes, 1) primary contact recreation and cost, and 2) secondary contact recreation and cost. For primary contact recreation and cost, the assessed indifference point is 5 million dollars and a category 2.5. For secondary contact recreation and cost, the assessed indifference point is 5 million dollars and a category 2.3. The weights were calculated using these indifference points and the value function. Given Dr. Peterson's current rankings and the weights calculated from the indifference points, his rankings and weights are consistent.

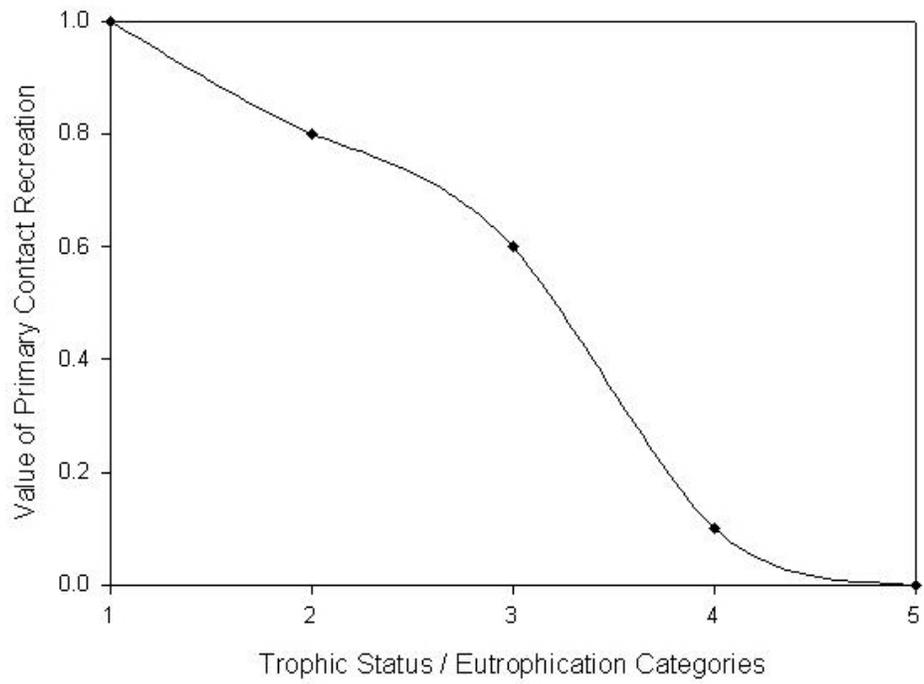
**Table 22: Charles H. Peterson's Trade-offs between Attributes**

	Ranking	Weights
Primary Contact Recreation	1	0.37
Secondary Contact Recreation	2	0.33
Cost	3	0.3

## ***D.4 Forrest R. Westall's Value Assessment***

### **D.4.1 Primary Contact Recreation**

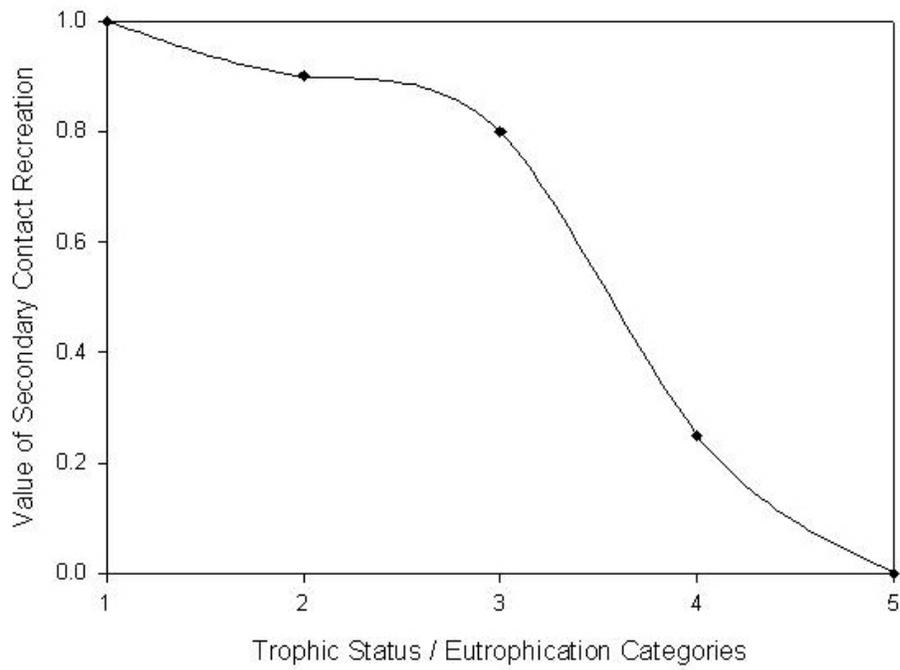
Figure 28 describes the values that Mr. Westall relayed during the interview for primary contact recreation for the given trophic status categories. As this function indicates, Mr. Westall thought that for primary contact recreation a trophic status 3 was closer in value to the ideal trophic category, 1, than the worst trophic category 5. Additionally, Mr. Westall thought that a category 2 was closer to a 1 than a 3 and that a category 4 was closer in value to a 5 than a 3. This was confirmed through his explanation that there was not a large loss in value for primary contact recreation until the category dropped below a 3, with a category 3 being 60% of the value of the best and a category 4 being only 10% of the value of the best. After more specifically defining the values, 1 was the best at a value of 1, 2 was 0.8, 3 was 0.6, 4 was 0.1, and 5 was the worst level for a value of 0.



**Figure 28: Value of Primary Contact Recreation for the Eutrophication Status Categories Forrest R. Westall**

## D.4.2 Secondary Contact Recreation

Figure 29 describes the values that Mr. Westall relayed during the interview for secondary contact recreation for the given trophic status / eutrophication categories. As this function indicates, Mr. Westall thought that, in comparison to primary contact recreation, that secondary contact recreation retains more of its value for trophic status / eutrophication categories 2, 3, and 4. For secondary contact recreation, Mr. Westall thought that there was not a large loss of value until a reservoir dropped below a category 3. This is indicated with a category 2 being 90% of the value of the best and a category 3 being 80% of the value of the best. Once a reservoir drops below a category 3, then there is a significant drop in value with a category 4 being only 25% of the value of the best. Therefore the values were: 1 was the best at a value of 1, 2 was 0.9, 3 was 0.8, 4 was 0.25, and 5 was the worst level for a value of 0.



**Figure 29: Value of Secondary Recreation for the Eutrophication Status Categories  
Forrest R. Westall**

### D.4.3 Cost

Mr. Westall said that his value function for cost is linear because there is the same loss of value going from 0 to 2.5 million as from 2.5 to 5 million, making 2.5 million the midpoint value. More specifically defining the values, 0 cost was the best at a value of 1, 1.25 million was .75, 2.5 million was .5, 3.75 million was 0.25, and 5 was the worst level for a value of 0.

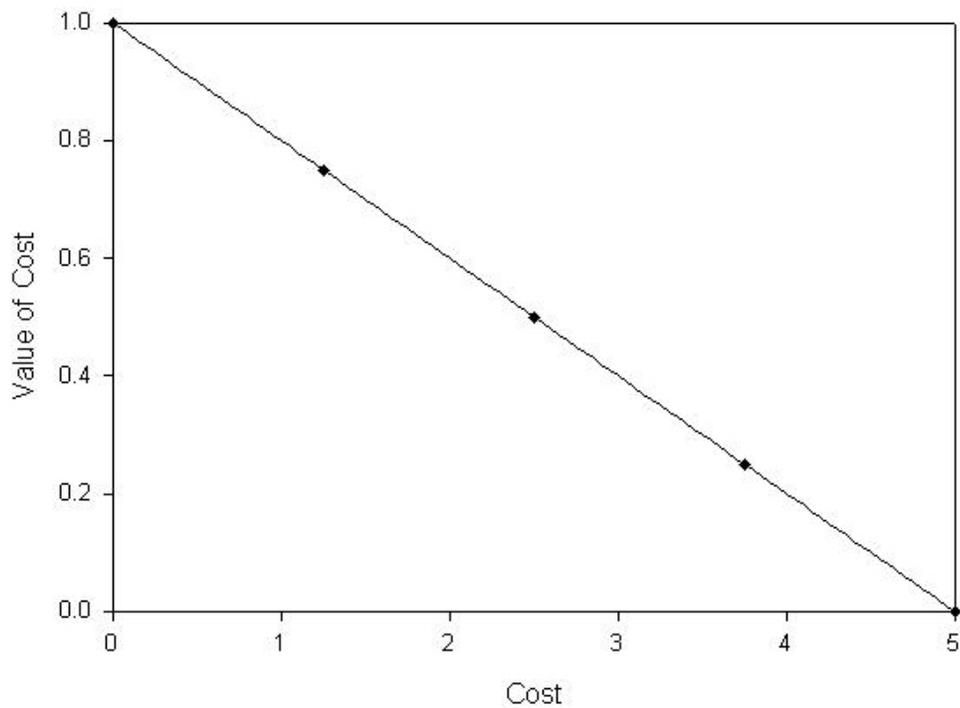


Figure 30: Value of Cost Forrest R. Westall

#### D.4.4 Trade-offs between Attributes

The weights were calculated by determining indifference points between two of the attributes, 1) primary contact recreation and cost, and 2) secondary contact recreation and cost. For primary contact recreation and cost, the assessed indifference point is 5 million dollars and a category 3. For secondary contact recreation and cost, the assessed indifference point is 5 million dollars and a category 3. The weights were calculated using these indifference points and the value function. Given Mr. Westall's current rankings and the weights calculated from the indifference points, his rankings and weights are consistent.

**Table 23: Forrest R. Westall's Trade-offs between Attributes**

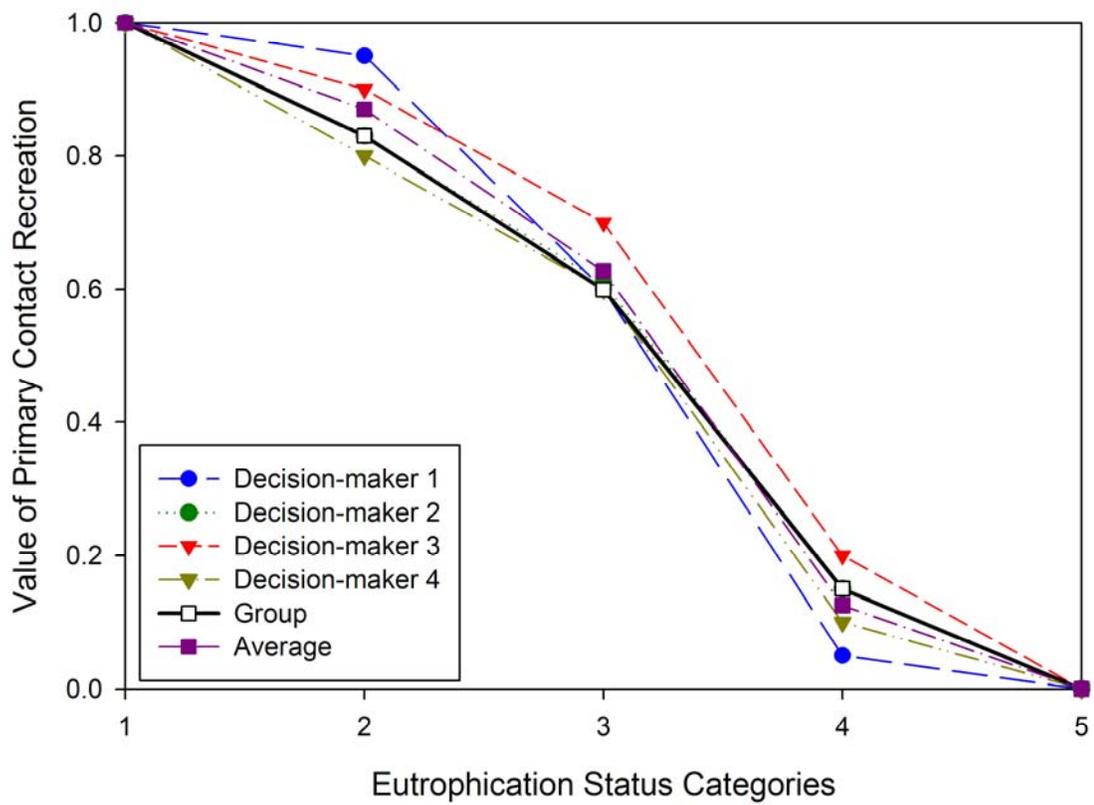
	Ranking	Weights
Primary Contact Recreation	1	0.43
Secondary Contact Recreation	2	0.32
Cost	3	0.25

***D.5: Group Value Assessment for North Carolina Nutrient  
Criteria by Marion E. Deerhake, Charles H. Peterson, Forrest R.  
Westall***

The purpose of this meeting was to gather the majority of the NC EMC study participants and attempt to reconcile disagreements between individual assessments to come to consensus. We focused on the areas of greatest disagreement. The participants were Marion Deerhake, Charles Peterson, Forrest Westall (referred to as the group); David Moreau was unable to attend.

### **D.5.1 Primary Contact Recreation**

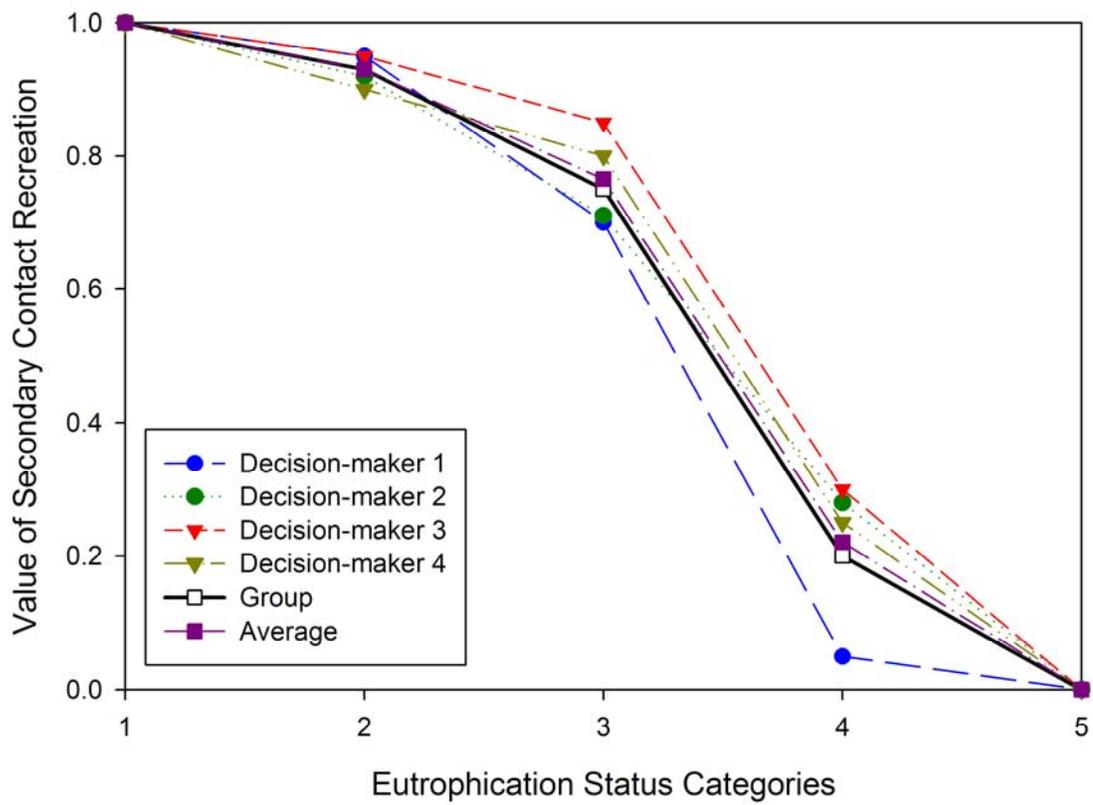
Figure 31 describes the values that the group relayed during the interview for primary contact recreation for the given trophic status categories (black line); the other functions are those of the individual and the mean value. Focusing on the group function, all members agreed that the best level was a category 1 and the worst level was a category 5. Additionally, for primary contact recreation, the group agreed that a category 3 was 60% of the value of the best. The values for category 2 and category 4 were the primary areas of disagreement. The group determined that for a category 2, there is a 17% loss in value; this value represents a compromise of values between a 5% to a 20% loss. The determination of 17% was the result of a group discussion leading to an agreement that there is a large enough difference between a category 1 and 2 for primary contact recreation that it would lead to a noticeable loss in value. Similarly there was a discussion for the value of category 4. The group all agreed that there is a significant loss in value beyond a category 3. The group determined that the value was in between the minimum and maximum individual values, and they provided an assessment stating that it retained 15% of the minimum value. In summary, the group values are: category 1 was the best at a value of 1, category 2 was 0.83, category 3 was 0.6, category 4 was 0.15, and category 5 was the worst level for a value of 0.



**Figure 31: Value Function for Primary Contact Recreation for a Range of Eutrophication Status Using All Decision-makers**

## D.5.2 Secondary Contact Recreation

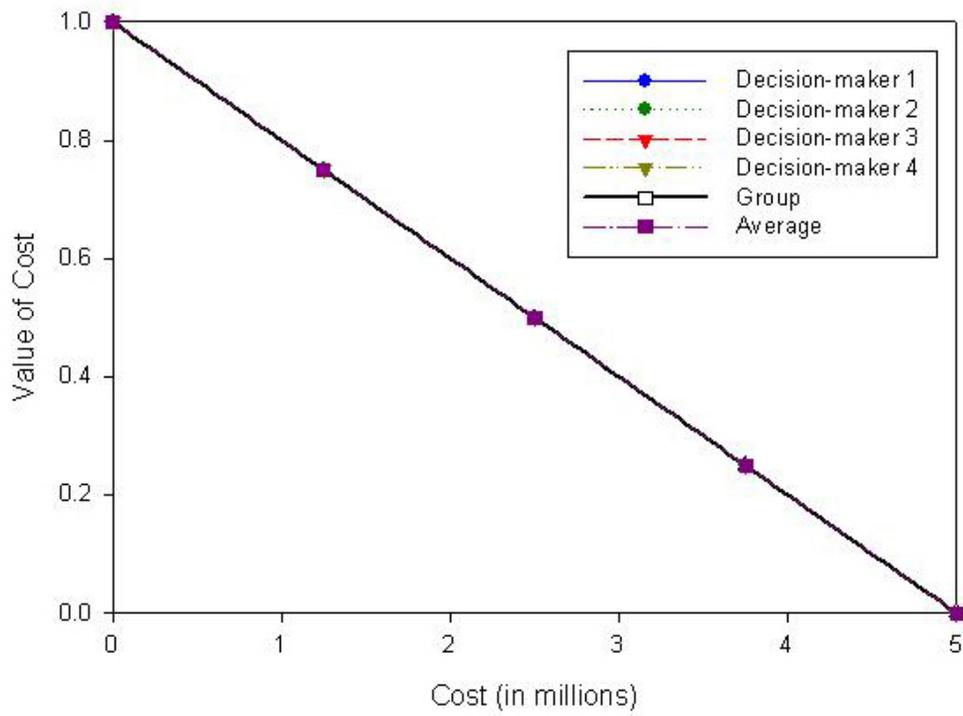
Figure 32 describes the values that the group relayed during the interview for primary contact recreation for the given trophic status categories (black line); the other functions are those of the individual and the mean value. Focusing on the group function, all members agreed that the best level was a category 1 and the worst level was a category 5. Also, for category 2, since all the individual values were between 95% and 90%, the group decided that the value should be the average of all the NC EMC participants. For secondary contact recreation, the areas of greatest disagreement were categories 3 and 4. For category 3, after Decision-maker 1 changed his assessment to a value that was that was more consistent with his judgments; the group then agreed that the value of a category 3 was 25% less than the best value. For a category 4, the group determined that, for secondary contact recreation, 20% of the minimum value was retained. Given that all the group members agreed that secondary contact recreation was a less sensitive use than primary contact recreation, the agreed upon values for all the categories are consistent when comparing them to the agreed upon values for primary contact recreation. In summary, the group values are: category 1 was the best at a value of 1, category 2 was 0.93, category 3 was 0.75, category 4 was 0.2, and category 5 was the worst level for a value of 0.



**Figure 32: Value Function for Secondary Contact Recreation for a Range of Eutrophication Status Using All Decision-makers**

### **D.5.3 Cost**

Figure 33 describes the values that the group relayed during the interview for primary contact recreation for the given trophic status categories (black line); the other functions are those of the individual and the mean value. Focusing on the group function, all members agreed that their value function for cost was linear with 0 cost being the best situation and \$5 million cost being the worst situation. Since all the experts had exactly the same function, they confirmed that the group value function was linear with the same values. They also agreed that there was no difference between a risky and a certain choice, meaning that their value function and utility function are more or less the same. More specifically defining the values for the group, 0 cost was the best at a value of 1, 1.25 million was .75, 2.5 million was .5, 3.75 million was 0.25, and 5 was the worst level for a value of 0.



**Figure 33: Value Function for Cost Using All Decision-Makers**

#### D.5.4 Trade-offs between Attributes

The weights were calculated by determining indifference points between two of the attributes, 1) primary contact recreation and cost, and 2) secondary contact recreation and cost. For primary contact recreation and cost, the assessed indifference point is 5 million dollars and a category 2.75; this indifference point is the average of the NC EMC study participants. For secondary contact recreation and cost, the assessed indifference point is 5 million dollars and a category 3; this was a value that was agreed upon by all the group members. The weights were calculated using these indifference points and the group value function. Given the group's current rankings and the weights calculated from the indifference points, their rankings and weights are consistent.

**Table 24: Group Trade-offs between Attributes**

	Ranking	Weights
Primary Contact Recreation	1	0.39
Secondary Contact Recreation	2	0.35
Cost	3	0.26

## Appendix E: North Carolina Lake Descriptive Statistics

**Table 25: Select Summary Statistics and Designated Uses for All Lakes and Reservoirs in the Blue Ridge Ecoregion of North Carolina.**

Lake	Ecoregion	Designated Uses	N	Chlorophyll a	DO	TP	TN	Secchi	Comments
Allen Creek Reservoir	Blue Ridge		26	3.04 (2.24)	8.14 <sup>1</sup> (.440)	.014 (.006)	.212 (.076)	3.34 (.877)	<sup>1</sup> missing 1 value
Appalachia Lake	Blue Ridge		12	2.78 <sup>1</sup> (1.86)	8.23 (.962)	.013 (.005)	.308 (.091)	3.54 (1.47)	<sup>1</sup> missing 3 values
ASU	Blue Ridge		7	3.33 <sup>1</sup> (1.15)	7.80 (.412)	.016 (.005)	.277 (.083)	4.74 (.535)	<sup>1</sup> missing 4 values
Bear Creek	Blue Ridge		27	26.1 <sup>1</sup> (16.9)	8.13 (.842)	.044 (.020)	.556 (.148_)	.926 (.189)	<sup>1</sup> missing 6 values
Bear Creek Reservoir	Blue Ridge		10	2.75 <sup>1</sup> (1.50)	8.20 (.350)	.015 (.008)	.200 (.074)	3.05 (.628)	<sup>1</sup> missing 6 values
Bee Tree Reservoir	Blue Ridge		5	3.50 <sup>1</sup> (3.54)	7.86 (.305)	.010 (0.00)	.236 (.049)	4.80 (.283)	<sup>1</sup> missing 3 values
Burnett Reservoir	Blue Ridge		16	2.20 <sup>1</sup> (1.32)	7.86 (.582)	.014 (.005)	.274 (.077)	6.90 (2.28)	<sup>1</sup> missing 6 values
Busbee Reservoir	Blue Ridge		1	8.00 (NA)	8.9 (NA)	.010 (NA)	.210 (NA)	1.70 (NA)	
Calderwood Lake	Blue Ridge		4	1.25 (.500)	8.73 (.299)	.015 (.006)	.280 (.054)	4.13 (2.36)	

Cedar Cliff Lake	Blue Ridge	21	3.21 <sup>1</sup> (1.72)	8.39 <sup>2</sup> (.798)	.012 (.005)	.179 (.141)	3.19 (1.29)	<sup>1</sup> missing 7 values <sup>2</sup> missing 2 values
Chatuge Lake	Blue Ridge	15	4.22 <sup>1</sup> (2.39)	7.99 (0.53)	.019 (.020)	.213 (.134)	2.75 (.0713)	<sup>1</sup> missing 6 values
Hiwassee Reservoir	Blue Ridge	70	2.38 <sup>1</sup> (1.26)	8.41 (.633)	.013 (.005)	.202 (.084)	3.27 (.771)	<sup>1</sup> missing 5 values
Kenilworth Lake	Blue Ridge	12	12.3 (11.9)	8.15 <sup>1</sup> (1.10)	.039 <sup>2</sup> (.017)	.486 (.108)	1.47 (.596)	<sup>1</sup> missing 1 value <sup>2</sup> missing 2 values
Lake Cheoah	Blue Ridge	9	1.00 <sup>1</sup> (0.00)	9.31 (.525)	.016 (.009)	.323 (.083)	5.10 (1.83)	<sup>1</sup> missing 3 values
Lake Emory	Blue Ridge	6	11.3 (11.7)	8.20 (.522)	.095 (.068)	.392 (.153)	.583 (.172)	
Lake Fontana	Blue Ridge	18	3.39 (1.42)	7.96 (1.47)	.011 (.002)	.230 (.110)	3.99 (.732)	
Lake James	Blue Ridge	99	4.45 <sup>1</sup> (5.09)	8.48 (.869)	.020 (.020)	.236 (.126)	3.33 (1.36)	<sup>1</sup> missing 19 values
Lake Julian	Blue Ridge	15	4.20 (2.34)	6.26 (.532)	.016 (.005)	.406 (.273)	3.42 (1.35)	
Lake Junaluska	Blue Ridge	34	16.4 <sup>1</sup> (12.5)	9.17 (.870)	.028 (.017)	.581 (.452)	1.30 (.547)	<sup>1</sup> missing 9 values

	Lake Rhodiss								<sup>1</sup> missing 34 values
		Blue Ridge	132	13.79 <sup>1</sup> (9.65)	9.36 <sup>2</sup> (2.02)	.050 <sup>3</sup> (.034)	.434 <sup>4</sup> (.168)	.902 <sup>5</sup> (.417)	<sup>2</sup> missing 23 values
									<sup>3</sup> missing 3 values
									<sup>4</sup> missing 10 values
									<sup>5</sup> missing 23 values
	Lake Santeetlah	Blue Ridge	33	3.74 <sup>1</sup> (1.60)	7.99 <sup>2</sup> (.491)	.015 (.007)	.231 (.087)	3.53 (1.04)	<sup>1</sup> missing 10 values
									<sup>2</sup> missing 3 values
	Lake Sequoya	Blue Ridge	15	12.3 <sup>1</sup> (9.37)	8.53 (.448)	.035 (.018)	.351 (.180)	1.09 (.242)	<sup>1</sup> missing 9 values
	Lake Tahoma	Blue Ridge	10	3.40 (2.37)	8.03 (.231)	.015 (.005)	.142 (.047)	4.66 (1.13)	
									<sup>1</sup> missing 8 values
	Nantahala Lake	Blue Ridge	47	1.23 <sup>1</sup> (.536)	7.85 <sup>2</sup> (.470)	.015 (.014)	.137 (.066)	5.42 <sup>3</sup> (1.38)	<sup>2</sup> missing 4 values
									<sup>3</sup> missing 2 values
	Thorpe Reservoir	Blue Ridge	36	3.76 <sup>1</sup> (1.79)	8.18 (.250)	.015 (.015)	.167 (.062)	4.02 (1.60)	<sup>1</sup> missing 11 values
	Waterville Reservoir	Blue Ridge	17	32.5 (23.0)	9.84 (2.45)	.097 (.049)	.749 (.391)	.941 (.339)	

Wolf Creek Reservoir	Blue Ridge	10	NA <sup>1</sup> (NA)	8.34 (.389)	.013 <sup>2</sup> (.007)	.171 (.071)	4.25 (1.66)	<sup>1</sup> missing 10 values <sup>2</sup> missing 1 value
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Key for Designated Uses in North Carolina: 1 = Primary recreation, 2 = Secondary recreation, 3 = Water supply, 4 = Nutrient sensitive water, 5 = Trout water, 6 = Critical area, 7 = Swamp water, 8 = Outstanding resource water

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**Table 26: Select Summary Statistics and Designated Uses for All Lakes and Reservoirs in the Piedmont Ecoregion of North Carolina.**

Lake	Ecoregion	Designated Uses	N	Chlorophyll 1 a	DO	TP	TN	Secchi	Comments
Apex Reservoir	Piedmont	3,4	3	9.50 <sup>1</sup> (3.53)	7.57 (.577)	.053 (.021)	.780 (.204)	.733 (.378)	<sup>1</sup> missing 1 value
Back Creek Lake	Piedmont	NA	NA	NA	NA	NA	NA	NA	
Badin Lake	Piedmont		99	17.1 <sup>1</sup> (11.5)	8.22 <sup>2</sup> (2.03)	.027 <sup>3</sup> (.022)	.487 <sup>4</sup> (.411)	1.15 <sup>5</sup> (.363)	<sup>1</sup> missing 15 values <sup>2</sup> missing 2 values <sup>3</sup> missing 1 value <sup>4</sup> missing 1 value <sup>5</sup> missing 2 values
Bass lake	Piedmont		4	14.8 (9.00)	7.65 (.252)	.060 (0.00)	.460 (.058)	.825 (.126)	
Beaverdam Lake	Piedmont		8	10.0 (12.7)	9.11 (1.96)	.081 (.016)	.450 (.180)	.388 (.125)	

354	Belews Lake								<sup>1</sup> missing 24 values		
		Piedmont		78	2.02 <sup>1</sup> (1.50)	7.13 (.836)	.013 <sup>2</sup> (.005)	.243 <sup>3</sup> (.096)	3.60 (.740)	<sup>2</sup> missing 1 value	
										<sup>3</sup> missing 1 value	
		Bassemmer City Lake			5	7.40 (5.94)	7.90 (.458)	.014 (.005)	.230 (.110)	2.68 (.390)	
		Big Lake	1,4		16	9.87 <sup>1</sup> (2.36)	7.37 (1.77)	.069 (.091)	.516 (.179)	.700 (.381)	<sup>1</sup> missing 8 values
		Blewett Falls Lake			10	24.4 <sup>1</sup> (18.2)	8.81 (2.19)	.061 (.024)	.701 (.359)	.880 (.494)	<sup>1</sup> missing 3 values
		Buckhorn Reservoir			6	21.2 (17.6)	7.12 (1.23)	.088 (.026)	.565 (.050)	.767 (.225)	
		Burlington Reservoir			20	23.1 <sup>1</sup> (14.7)	7.49 (1.11)	.032 (.010)	.497 (.248)	1.00 (.287)	<sup>1</sup> missing 6 values
		Cane Creek Reservoir			33	43.5 <sup>1</sup> (48.3)	8.47 (.864)	.026 (.012)	.462 (.150)	1.19 (.389)	<sup>1</sup> missing 18 values
		Carthage City Lake			8	3.80 <sup>1</sup> (2.05)	6.53 (.892)	.026 (.017)	.251 (.105)	2.35 (.765)	<sup>1</sup> missing 3 values
		Clearwater Lake			2	23.5 (4.95)	8.85 (.495)	.040 (.014)	.460 (.071)	1.15 (.212)	
		Corporation Lake		3,4,6	12	9.50 <sup>1</sup> (4.67)	7.18 (1.37)	.055 (.021)	.585 (.150)	.683 (.251)	<sup>1</sup> missing 6 values

Falls Lake									<sup>1</sup> missing 84 values
	Piedmont	1,3,4,6	659	35.4 <sup>1</sup> (39.8)	8.48 <sup>2</sup> (2.03)	.096 <sup>3</sup> (.123)	.768 (.793)	.593 (.332)	<sup>2</sup> missing 11 values
									<sup>3</sup> missing 3 values
Farmer Lake	Piedmont		39	16.2 <sup>1</sup> (12.5)	8.12 (1.13)	.034 (.025)	.376 (.166)	1.23 (.689)	<sup>1</sup> missing 16 values
Graham-Meban Reservoir	Piedmont		35	29.3 <sup>1</sup> (25.2)	8.04 (1.20)	.055 (.027)	.492 (.187)	.680 (.225)	<sup>1</sup> missing 15 values
Hanging Rock Lane	Piedmont		25	8.59 <sup>1</sup> (12.8)	7.92 <sup>2</sup> (.555)	.020 (.009)	.223 (.074)	3.24 (.792)	<sup>1</sup> missing 8 values <sup>2</sup> missing 1 value
Harris Lake	Piedmont		39	15.5 <sup>1</sup> (6.97)	7.94 (.914)	.029 (.009)	.477 (.119)	1.64 (.334)	<sup>1</sup> missing 3 values
High Point Reservoir	Piedmont		75	11.1 <sup>1</sup> (5.36)	7.74 (.998)	.022 (.014)	.384 (.236)	1.24 (.420)	<sup>1</sup> missing 33 values
High Rock Lake	Piedmont	1,3	190	31.7 <sup>1</sup> (19.2)	8.99 <sup>2</sup> (1.76)	.091 (.063)	.798 (.390)	.614 (.240)	<sup>1</sup> missing 70 values <sup>2</sup> missing 6 values
Hyc0 Lake	Piedmont		48	4.00 <sup>1</sup> (2.97)	6.78 (.540)	.025 (.054)	.308 (.124)	1.99 (.566)	<sup>1</sup> missing 12 values

Jordan Lake									<sup>1</sup> missing 350 values
	Piedmont		1299	37.1 <sup>1</sup> (39.9)	9.26 <sup>2</sup> (2.13)	.090 <sup>3</sup> (.071)	.820 <sup>4</sup> (.767)	.646 (.425)	<sup>2</sup> missing 7 values <sup>3</sup> missing 23 values <sup>4</sup> missing 24 values
Kannapolis Lake	Piedmont		10	15.3 <sup>1</sup> (8.66)	8.63 (1.30)	.033 (.013)	.442 (.216)	.960 (.276)	<sup>1</sup> missing 6 values
Kernersville Reservoir	Piedmont		10	9.75 <sup>1</sup> (4.92)	7.70 (.562)	.033 (.008)	.478 (.175)	.920 (.249)	<sup>1</sup> missing 6 values
Kerr Lake	Piedmont		52	11.9 <sup>1</sup> (10.5)	8.15 (.797)	.024 <sup>2</sup> (.018)	.635 (1.11)	1.60 (.535)	<sup>1</sup> missing 13 values <sup>2</sup> missing 1 value
Kerr Scott Reservoir	Piedmont	1,3,5	48	6.60 <sup>1</sup> (2.81)	8.52 (.750)	.018 (.008)	.254 (.093)	1.95 (.580)	<sup>1</sup> missing 15 values
Kings Mountain Reservoir	Piedmont	3,6	56	7.48 <sup>1</sup> (5.39)	8.44 (.507)	.015 (.008)	.343 (.130)	1.77 (.701)	<sup>1</sup> missing 13 values
Lake Adger	Piedmont	2	9	8.16 <sup>1</sup> (3.60)	8.42 (.570)	.018 (.011)	.196 (.048)	1.40 (.690)	<sup>1</sup> missing 3 values
Lake Benson	Piedmont	3,4,6	20	20.6 <sup>1</sup> (15.3)	8.49 (1.74)	.043 (.017)	.426 <sup>2</sup> (.101)	.820 (.483)	<sup>1</sup> missing 6 values <sup>2</sup> missing 1 value

Lake Brandt	Piedmont		30	28.9 <sup>1</sup> (18.4)	8.45 (1.01)	.042 (.017)	.435 (.134)	.907 (.241)	<sup>1</sup> missing 9 values
Lake Bunch	Piedmont	3,6	19	15.4 <sup>1</sup> (11.5)	7.89 (1.49)	.027 (.015)	.375 (.170)	3.11 (1.07)	<sup>1</sup> missiing 5 values
Lake Burlington	Piedmont		16	26.8 <sup>1</sup> (12.0)	7.68 (1.08)	.060 (.026)	.513 (.204)	.575 (.161)	<sup>1</sup> missing 5 values
Lake Butner	Piedmont	3.4	29	12.6 <sup>1</sup> (8.20)	7.99 (.870)	.027 (.018)	.390 (.130)	1.96 (.620)	<sup>1</sup> missing 4 values
Lake Concord	Piedmont		12	27.0 <sup>1</sup> (24.0)	8.15 (.518)	.061 (.017)	.498 (.095)	.575 (.160)	<sup>1</sup> missing 6 values
Lake Corriher	Piedmont		10	20.5 <sup>1</sup> (3.87)	8.07 (.883)	.067 (.033)	.481 (.126)	.960 (.272)	<sup>1</sup> missing 6 values
Lake Crabtree	Piedmont	1,4	21	27.7 <sup>1</sup> (17.5)	6.03 (1.36)	.101 (.035)	.727 (.220)	.262 (.097)	<sup>1</sup> missing 12 values
Lake Devin	Piedmont		16	35.7 <sup>1</sup> (42.0)	7.81 (1.60)	.044 (.021)	.527 (.106)	.856 (.193)	<sup>1</sup> missing 5 values
Lake Fisher	Piedmont		15	24.7 <sup>1</sup> (23.7)	8.21 (1.62)	.055 (.040)	.591 (.786)	.687 (.196)	<sup>1</sup> missing 9 values

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Lake Gaston	Piedmont	60	7358 <sup>1</sup> (5.01)	7.03 <sup>2</sup> (1.91)	.018 <sup>3</sup> (.010)	.547 <sup>4</sup> (.783)	1.64 <sup>5</sup> (.532)	<sup>1</sup> missing 27 values <sup>2</sup> missing 4 values <sup>3</sup> missing 1 value <sup>4</sup> missing 1 value <sup>5</sup> missing 4 values
Lake Hickory	Piedmont	58	21.1 <sup>1</sup> (22.4)	8.96 (1.65)	.033 <sup>2</sup> (.019)	.365 <sup>3</sup> (.143)	1.29 (.382)	<sup>1</sup> missing 15 values <sup>2</sup> missing 2 values <sup>3</sup> missing 2 values
Lake Higgins	Piedmont	16	18.4 <sup>1</sup> (9.78)	7.88 (.534)	.030 (.014)	.364 (.079)	1.05 (.301)	<sup>1</sup> missing 6 values
Lake Hunt	Piedmont	51	13.6 <sup>1</sup> (10.6)	8.67 (.942)	.030 (.018)	.367 (.147)	1.46 (.762)	<sup>1</sup> missing 9 values <sup>1</sup> missing 12 values
Lake Isaac Walton	Piedmont	18	21.8 <sup>1</sup> (13.6)	8.98 <sup>2</sup> (.874)	.021 (.013)	.356 (.125)	1.03 <sup>3</sup> (.353)	<sup>2</sup> missing 3 values <sup>3</sup> missing 3 values

Lake Johnson	Piedmont	1,4	10	6.80 (4.42)	7.61 (.687)	.028 (.007)	.405 (.173)	1.28 (.770)	
Lake Lee	Piedmont		15	29.7 <sup>1</sup> (26.7)	9.25 (2.50)	.138 (.035)	.907 (.262)	.473 (.139)	<sup>1</sup> missing 9 values
Lake Lure	Piedmont	1,5	27	8.05 <sup>1</sup> (4.24)	10.7 (5.93)	.017 (.008)	.279 (.082)	1.90 (.650)	<sup>1</sup> missing 10 values
Lake Mackintosh	Piedmont		82	26.6 <sup>1</sup> (14.4)	8.59 (1.20)	.035 (.031)	.491 (.259)	1.04 (.436)	<sup>1</sup> missing 53 values
Lake Michie	Piedmont	3,4	13	20.3 <sup>1</sup> (22.9)	8.17 <sup>2</sup> (.718)	.038 (.028)	.438 (.071)	1.15 (.648)	<sup>1</sup> missing 6 values <sup>2</sup> missing 3 values
Lake Monroe	Piedmont		10	25.3 <sup>1</sup> (18.5)	8.47 (2.13)	.080 (.036)	.882 (.326)	.730 (.206)	<sup>1</sup> missing 6 values <sup>1</sup> missing 24 values <sup>2</sup> missing 3 values
Lake Montonia	Piedmont		26	3.5 <sup>1</sup> (.707)	7.98 <sup>2</sup> (.973)	.019 <sup>3</sup> (.012)	.202 <sup>4</sup> (.074)	2.79 <sup>5</sup> (.525)	<sup>3</sup> missing 1 value <sup>4</sup> missing 1 value <sup>5</sup> missing 3 values

	Lake Norman	Piedmont		87	5.95 <sup>1</sup> (4.49)	7.88 (.832)	.015 <sup>2</sup> (.007)	.269 <sup>3</sup> (.151)	2.05 (.665)	<sup>1</sup> missing 24 values <sup>2</sup> missing 4 values <sup>3</sup> missing 4 values
	Lake Orange	Piedmont	3,4	15	24.7 <sup>1</sup> (31.7)	7.97 (.380)	.032 (.017)	.390 (.067)	1.51 (.470)	<sup>1</sup> missing 6 values
	Lake Raleigh	Piedmont		8	12.9 (6.77)	7.06 (2.79)	.041 (.031)	.400 (.081)	.650 (.256)	
	Lake Reese	Piedmont	3,6	39	16.5 <sup>1</sup> (9.05)	7.92 (.860)	.022 (.012)	.420 (.139)	1.15 (.450)	<sup>1</sup> missing 15 values
	Lake Rogers	Piedmont	3,4,6	5	32.7 <sup>1</sup> (31.5)	6.06 (1.16)	.102 (.041)	.850 (.150)	.320 (.110)	<sup>1</sup> missing 2 values
	Lake Roxboro	Piedmont		39	15.8 <sup>1</sup> (9.97)	8.50 (1.34)	.024 (.014)	.450 (.099)	1.40 (.504)	<sup>1</sup> missing 15 values
	Lake Summit	Piedmont	1,2,5	18	12.4 <sup>1</sup> (6.42)	11.4 (6.22)	.013 (.008)	.278 (.107)	2.14 (.866)	<sup>1</sup> missing 9 values
	Lake Thom-A-Lex	Piedmont	3,6	34	25.7 <sup>1</sup> (13.0)	8.71 (1.16)	.047 (.027)	.524 (.154)	.782 (.234)	<sup>1</sup> missing 12 values
	Lake Tilery	Piedmont		40	10.6 <sup>1</sup> (8.21)	7.88 (1.74)	.026 (.018)	.608 (.412)	1.38 (.562)	<sup>1</sup> missing 12 values
	Lake Townsend	Piedmont		24	19.3 <sup>1</sup> (8.08)	8.06 (.951)	.036 (.019)	.377 (.120)	.938 (.359)	<sup>1</sup> missing 9 values
	Lake Twitty	Piedmont		15	20.0 <sup>1</sup> (12.1)	9.85 (2.69)	.111 (.058)	.763 (.304)	.800 (.100)	<sup>1</sup> missing 9 values

	Lake Wendell	Piedmont		6	49.8 (62.2)	6.53 (2.92)	.308 (.108)	1.00 (.277)	.633 (.121)	
	Lake Wheeler	Piedmont	3,4	18	11.8 <sup>1</sup> (6.03)	7.67 (1.01)	.027 (.011)	.396 (.095)	1.05 (.330)	<sup>1</sup> missing 6 values
	Lake Wright	Piedmont		5	34.0 <sup>1</sup> (8.49)	9.38 (1.53)	.066 (.055)	.558 (.269)	1.16 (.680)	<sup>1</sup> missing 3 values
	Lake Wylie	Piedmont		147	15.7 <sup>1</sup> (9.11)	8.54 <sup>2</sup> (1.30)	.050 <sup>3</sup> (.036)	.411 <sup>4</sup> (.225)	1.10 <sup>5</sup> (.427)	<sup>1</sup> missing 37 values <sup>2</sup> missing 5 values <sup>3</sup> missing 1 value <sup>4</sup> missing 1 value <sup>5</sup> missing 1 value
	Lasater Lake	Piedmont		2	23.0 (17.0)	8.30 (.424)	.050 (0.00)	.435 (.035)	.600 (0.00)	
	Little River Dam	Piedmont		2	17.0 (9.90)	8.90 (.283)	.025 (.021)	.430 (.113)	1.20 (.424)	
	Little River Reservoir	Piedmont	3,4,6	51	13.5 <sup>1</sup> (8.88)	7.95 (2.07)	.028 (.016)	.440 (.138)	1.06 (.180)	<sup>1</sup> missing 24 values
	Long Lake	Piedmont	NA	NA	NA	NA	NA	NA	NA	
	Lookout Shoals Lake	Piedmont		36	9.89 <sup>1</sup> (10.0)	7.72 (1.60)	.021 (.008)	.398 (.126)	1.37 (.480)	<sup>1</sup> missing 9 values

Lower Moccasin Lake	Piedmont		2	46.5 (24.7)	10.2 (1.91)	.070 (.014)	.525 (.120)	1.55 (1.06)	
Maiden Lake	Piedmont		10	11.0 <sup>1</sup> (8.16)	7.97 (.646)	.113 (.234)	.523 (.354)	.500 (.271)	<sup>1</sup> missing 6 values
Mayo Reservoir	Piedmont		30	4.33 <sup>1</sup> (3.31)	7.96 (.600)	.016 (.010)	.231 (.080)	2.79 (.907)	<sup>1</sup> missing 9 values
McCrary Lake	Piedmont	3,6	10	11.0 <sup>1</sup> (7.68)	8.17 <sup>2</sup> (.760)	.024 (.016)	.417 (.110)	3.04 (.610)	<sup>1</sup> missing 5 values <sup>2</sup> missing 1 value
Mountain Island Lake	Piedmont		54	4.94 <sup>1</sup> (2.64)	7.38 (.674)	.016 (.008)	.340 (.240)	1.61 (.502)	<sup>1</sup> missing 18 values
Newton City Lake	Piedmont		4	3.00 (1.41)	7.70 (.804)	.015 (.006)	.568 (.490)	1.28 (.427)	
Pittsboro Lake	Piedmont		16	31.7 <sup>1</sup> (22.7)	7.66 (2.05)	.059 (.033)	.602 (.261)	.625 (.188)	<sup>1</sup> missing 5 values
Quaker Creek Reservoir	Piedmont	NA	NA	NA	NA	NA	NA	NA	
Reedy Creek Lake	Piedmont	1,4	5	6.00 <sup>1</sup> (0.00)	7.68 (1.67)	.044 (.025)	.432 (.110)	.980 (.672)	<sup>1</sup> missing 3 values
Reidsville Lake	Piedmont		20	23.4 <sup>1</sup> (18.8)	8.26 (.839)	.032 (.019)	.405 (.165)	1.36 (.868)	<sup>1</sup> missing 6 values
Richland Lake	Piedmont		6	9.50 (6.86)	7.67 (.787)	.022 (.010)	.328 (.045)	1.28 (.183)	

Roberdel Lake	Piedmont		8	10.8 <sup>1</sup> (10.4)	6.20 (.630)	.020 (.008)	.445 (.115)	.738 (.141)	<sup>1</sup> missing 4 values
Rock River Reservoir	Piedmont		16	34.6 <sup>1</sup> (10.3)	9.01 (1.56)	.133 (.074)	.946 (.362)	.531 (.140)	<sup>1</sup> missing 6 values
Rockingham City Lake	Piedmont		4	4.50 <sup>1</sup> (4.95)	3.18 (.544)	.025 (.006)	.435 (.096)	.750 (.252)	<sup>1</sup> missing 2 values
Ross Lake	Piedmont		1	18.0 (NA)	6.4 (NA)	.070 (NA)	.880 (NA)	.300 (NA)	
Salem Lake	Piedmont		51	29.9 <sup>1</sup> (33.4)	7.89 (1.22)	.034 <sup>2</sup> (.016)	.411 (.158)	.978 (.308)	<sup>1</sup> missing 18 values <sup>2</sup> missing 1 value
Sandy Creek Reservoir	Piedmont		24	25.6 <sup>1</sup> (27.7)	9.41 (1.64)	.071 (.035)	.694 (.361)	1.01 (.242)	<sup>1</sup> missing 9 values
Sycamore Lake	Piedmont	1,4	5	40.0 <sup>1</sup> (41.0)	7.24 (1.80)	.038 (.029)	.568 (.204)	.860 (.536)	<sup>1</sup> missing 3 values
Tuckertown Reservoir	Piedmont		18	31.5 <sup>1</sup> (16.3)	8.34 (2.99)	.063 (.024)	.779 (.455)	.750 (.367)	<sup>1</sup> missing 6 values
University Lake	Piedmont		16	56.1 <sup>1</sup> (46.5)	8.79 (1.09)	.064 (.020)	.591 (.216)	.663 (.189)	<sup>1</sup> missing 6 values
Upper Moccasin	Piedmont		4	40.0 (38.6)	9.75 (2.26)	.055 (.045)	.613 (.298)	1.53 (1.12)	
Wadesboro City Reservoir	Piedmont		10	12.0 <sup>1</sup> (4.08)	8.41 (.936)	.041 (.014)	.506 (.436)	.910 (.463)	<sup>1</sup> missing 6 values

Water Lake	Piedmont		20	8.56 <sup>1</sup> (3.58)	7.67 (1.25)	.018 <sup>2</sup> (.016)	.595 <sup>3</sup> (.358)	1.16 (.317)	<sup>1</sup> missing 4 values <sup>2</sup> missing 1 value <sup>3</sup> missing 1 value
Winston Lake	Piedmont	2	10	14.7 <sup>1</sup> (8.08)	8.38 (.950)	.033 (.018)	.641 <sup>2</sup> (.110)	.980 (.396)	<sup>1</sup> missing 7 values <sup>2</sup> missing 1 value

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Key for Designated Uses in North Carolina: 1 = Primary recreation, 2 = Secondary recreation, 3 = Water supply,  
4 = Nutrient sensitive water, 5 = Trout water, 6 = Critical area, 7 = Swamp water, 8 = Outstanding resource water

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**Table 27: Select Summary Statistics and Designated Uses for All Lakes and Reservoirs in the Southeastern Plain Ecoregion of North Carolina.**

Lake	Ecoregion	Designated Uses	N	Chlorophyll l a	DO	TP	TN	Secchi	Comments
Bonnie Doone Lake	Southeastern Plain		7	6.75 <sup>1</sup> (4.57)	7.27 (.711)	.036 (.038)	.463 (.275)	1.24 (.580)	<sup>1</sup> missing 3 values
Cliffs of the Neuse	Southeastern Plain	1,4	7	10.5 <sup>1</sup> (2.38)	8.28 (.410)	.014 (.008)	.260 (.084)	2.55 (.390)	<sup>1</sup> missing 3 values
Glenville Lake	Southeastern Plain		7	26.5 <sup>1</sup> (5.51)	8.01 (1.14)	.056 (.011)	.428 (.129)	.857 (.113)	<sup>1</sup> missing 3 values
Hamlet City Lake	Southeastern Plain		14	5.30 <sup>1</sup> (2.91)	5.56 (1.31)	.025 (.020)	.383 (.093)	1.21 (.332)	<sup>1</sup> missing 4 values
Holts Lake	Southeastern Plain		4	12.3 (6.90)	5.15 (.742)	.070 (.029)	.510 (.082)	.850 (.100)	
Hope Mills Lake	Southeastern Plain		8	21.8 <sup>1</sup> (20.3)	7.99 (1.17)	.044 (.013)	.550 (.116)	.838 (.250)	<sup>1</sup> missing 3 values
Johns Pond	Southeastern Plain		3	70.3 (8.74)	5.80 (2.26)	.373 (.178)	.710 (.100)	.800 (.300)	
Kornbow Lake	Southeastern Plain		7	11.8 <sup>1</sup> (5.19)	7.13 (.544)	.026 (.017)	.497 (.143)	1.81 (.418)	<sup>1</sup> missing 3 values
Lake Ben Johnson	Southeastern Plain	3,4,6	6	11.3 <sup>1</sup> (5.13)	6.18 (1.36)	.062 <sup>2</sup> (.035)	.554 <sup>3</sup> (.153)	.810 (.213)	<sup>1</sup> missing 3 values <sup>2</sup> missing 1 value <sup>3</sup> missing 1 value
Lake Tabor	Southeastern Plain		13	56.3 <sup>1</sup> (57.4)	7.79 (2.51)	.064 (.030)	.549 (.229)	1.11 (.582)	<sup>1</sup> missing 5 values

Lake Wilson	Southeastern Plain	3,4	5	14.5 <sup>1</sup> (6.36)	7.92 (.311)	.084 (.028)	.626 (.090)	.660 (.089)	<sup>1</sup> missing 3 values
Maxton Pond	Southeastern Plain		4	20.0 <sup>1</sup> (19.5)	6.15 (2.31)	.213 (.235)	1.34 (1.51)	.825 (.126)	<sup>1</sup> missing 1 value
Mintz Pond	Southeastern Plain		7	6.00 <sup>1</sup> (1.83)	4.73 (1.31)	.050 (.017)	.389 (.120)	1.13 (.076)	<sup>1</sup> missing 3 values
Mott Lake	Southeastern Plain		20	5.11 <sup>1</sup> (11.9)	6.65 (.742)	.015 (.011)	.271 (.116)	1.56 (.361)	<sup>1</sup> missing 2 values
Old Town Reservoir	Southeastern Plain		32	7.81 <sup>1</sup> (6.11)	7.60 (.596)	.020 <sup>2</sup> (.014)	.293 (.118)	1.60 (.639)	<sup>1</sup> missing 6 values <sup>2</sup> missing 1 value
Pages Lake	Southeastern Plain		11	6.82 (2.96)	5.66 (.604)	.031 (.019)	.454 (.077)	1.52 (.244)	
Roanoke Rapids Lake	Southeastern Plain		29	6.37 <sup>1</sup> (5.00)	7.12 (1.35)	.033 (.077)	.474 (.568)	1.61 (.469)	<sup>1</sup> missing 10 values
Tar River Reservoir	Southeastern Plain		32	28.9 <sup>1</sup> (13.5)	7.72 (1.33)	.052 (.023)	.422 (.116)	.684 (.182)	<sup>1</sup> missing 12 values
Toisnot Reservoir	Southeastern Plain	3,4,6	9	15.2 <sup>1</sup> (14.4)	4.07 (1.53)	.123 (.062)	.643 (.148)	.633 (.166)	<sup>1</sup> missing 4 values
White Millspond	Southeastern Plain		4	108 (103)	4.55 (1.23)	.233 (.102)	.698 (.119)	.600 (.115)	
Wiggins Mill Reservoir	Southeastern Plain	3,4,6	12	35.7 <sup>1</sup> (26.5)	6.83 (.980)	.073 (.040)	.535 (.156)	6.83 (.150)	<sup>1</sup> missing 6 values

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Key for Designated Uses in North Carolina: 1 = Primary recreation, 2 = Secondary recreation, 3 = Water supply, 4 = Nutrient sensitive water, 5 = Trout water, 6 = Critical area, 7 = Swamp water, 8 = Outstanding resource water

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**Table 28: Select Summary Statistics and Designated Uses for All Lakes and Reservoirs in the Middle Atlantic Coastal Plain Ecoregion of North Carolina.**

Lake	Ecoregion	Designated Uses	N	Chlorophyll a	DO	TP	TN	Secchi	Comments
Alligator Lake	Mid-Atlantic Coastal Plain		2	7.00 (0.00)	7.00 (0.00)	.100 (.028)	.740 (.071)	.300 (0.00)	
Bay Tree Lake	Mid-Atlantic Coastal Plain		20	4.71 <sup>1</sup> (4.65)	7.60 (.322)	.028 (.031)	.298 (.284)	1.17 (.493)	<sup>1</sup> missing 6 values
Boiling Springs Lake	Mid-Atlantic Coastal Plain		24	3.07 <sup>1</sup> (2.15)	6.48 (.669)	.020 (.013)	.508 (.218)	.638 (.270)	<sup>1</sup> missing 9 values
Cabin Lake	Mid-Atlantic Coastal Plain		13	48.8 (69.5)	5.44 (1.11)	.220 (.098)	1.44 (.421)	.315 (.038)	
Catfish Lake	Mid-Atlantic Coastal Plain		6	3.50 (1.97)	7.65 (.302)	.020 (0.00)	.508 (.075)	.500 (.126)	
Ellis Lake	Mid-Atlantic Coastal Plain		2	1.00 (0.00)	7.30 (.980)	.010 (0.00)	.260 (.071)	.800 (.141)	
Great Lake	Mid-Atlantic Coastal Plain		6	6.00 (3.58)	7.18 (1.04)	.038 (.008)	.418 (.133)	.267 (.052)	
Greenfield Lake	Mid-Atlantic Coastal Plain		18	29.8 <sup>1</sup> (36.3)	5.99 (3.37)	.081 (.057)	.537 (.201)	1.28 (.190)	<sup>1</sup> missing 6 values

Jones Lake	Mid-Atlantic Coastal Plain		34	1.67 <sup>1</sup> (1.20)	6.70 (.661)	.016 (.008)	.470 (.190)	.885 (.597)	<sup>1</sup> missing 10 values
Lake Mattamuskeet	Mid-Atlantic Coastal Plain		22	9.11 <sup>1</sup> (7.45)	8.00 (1.11)	.035 (.017)	.976 (.679)	.570 <sup>2</sup> (.270)	<sup>1</sup> missing 4 values <sup>2</sup> missing 2 values
Lake Phelps	Mid-Atlantic Coastal Plain	2,7,8	66	2.74 <sup>1</sup> (2.00)	7.94 (.510)	.017 (.013)	.298 (.230)	1.53 (.390)	<sup>1</sup> missing 15 values
Lake Waccamaw	Mid-Atlantic Coastal Plain		41	3.53 <sup>1</sup> (2.91)	7.54 (.535)	.020 (.015)	.453 (.129)	1.56 (.531)	<sup>1</sup> missing 9 values
Lake Wackena	Mid-Atlantic Coastal Plain		4	15.0 (9.83)	8.28 (.608)	.095 (.073)	.563 (.133)	.975 (.499)	
Limestone Lake	Mid-Atlantic Coastal Plain		35	9.31 (11.5)	7.97 (1.96)	.119 (.163)	1.06 (1.21)	.446 (.122)	
Merchants Millpond	Mid-Atlantic Coastal Plain	4,6	15	21.1 (13.4)	3.14 (2.08)	.090 (.029)	.670 (.098)	.600 <sup>1</sup> (.320)	<sup>1</sup> missing 2 values
Pungo Lake	Mid-Atlantic Coastal Plain		8	17.1 (20.4)	6.93 (.578)	.263 (.128)	2.55 (.934)	.100 (0.00)	
Salters Lake	Mid-Atlantic Coastal Plain		18	7.75 <sup>1</sup> (6.34)	6.91 (.658)	.021 (.007)	.427 (.117)	.778 (.414)	<sup>1</sup> missing 6 values
Singletary Lake	Mid-Atlantic Coastal Plain		26	7.47 <sup>1</sup> (6.39)	7.28 (.571)	.020 (.008)	.331 (.065)	.858 (.387)	<sup>1</sup> missing 9 values
Swan Creek	Mid-Atlantic Coastal Plain		3	1.00 (0.00)	4.60 (1.80)	.030 (0.00)	.803 (.095)	.300 (0.00)	
White Lake	Mid-Atlantic Coastal Plain		63	2.43 <sup>1</sup> (4.42)	7.60 (.580)	.013 (.005)	.141 (.067)	2.48 (.350)	<sup>1</sup> missing 9 values

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Key for Designated Uses in North Carolina: 1 = Primary recreation, 2 = Secondary recreation, 3 = Water supply, 4 = Nutrient sensitive water, 5 = Trout water, 6 = Critical area, 7 = Swamp water, 8 = Outstanding resource water

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**Table 29: Summary Statistics, Missingness, and Transformations for Select Water Quality Variables in the Blue Ridge Ecoregion**

Photic Variable and Units	N	Mean	Median	Standard Deviation	Maximum	Minimum	Skewness	Kurtosis	Transformation
TP (mg/L)	701	-1.72	-1.70	.316	-.721	-2.00	.925	.096	Log <sub>10</sub>
PO <sub>4</sub> (mg/L)	203	-1.95	-2.00	.182	-1.00	-2.00	3.68	13.3	Log <sub>10</sub>
TN (mg/L)	695	-.585	-.585	.264	.465	-1.70	-.114	.400	Log <sub>10</sub>
TON (mg/L)	689	-.807	-.770	.350	0.00	-3.00	-1.27	6.03	Log <sub>10</sub>
TIN (mg/L)	695	-1.21	-1.22	.475	.465	-2.00	.202	-.670	Log <sub>10</sub>
Chlorophyll a ( µg/L)	540	.648	.602	.480	1.91	0.00	.300	-.808	Log <sub>10</sub>
DO (mg/L)	669	8.50	8.30	1.28	14.7	2.60	.739	5.06	None
Temperature (C)	677	25.5	26.1	3.81	36.2	7.80	-1.48	4.80	None
Secchi (meters)	672	.332	.398	.329	1.08	-0.70	-.522	-.292	Log <sub>10</sub>
TSS (mg/L)	562	.452	.477	.395	1.78	0.00	.691	.112	Log <sub>10</sub>
Turbidity (NTU)	580	.373	.301	.353	1.78	0.00	.907	.238	Log <sub>10</sub>
Data Set Sample Size	706								

The summary statistics are provided using the transformed data.

**Table 30: Summary Statistics, Missingness, and Transformations for Select Water Quality Variables in the Southeastern Ecoregion.**

Photic Variable and Units	N	Mean	Median	Standard Deviation	Maximum	Minimum	Skewness	Kurtosis	Transformation
TP (mg/L)	234	-1.55	-1.52	.381	-.252	-2.00	.607	.019	Log <sub>10</sub>
PO <sub>4</sub> (mg/L)	56	-1.94	-2.00	.213	-.886	-2.00	3.97	15.9	Log <sub>10</sub>
TN (mg/L)	235	-.404	-.387	.213	.556	-0.959	.651	2.67	Log <sub>10</sub>
TON (mg/L)	233	-.524	-.523	.242	.531	-1.70	-.394	3.72	Log <sub>10</sub>
TIN (mg/L)	235	-1.24	-1.22	.445	.415	-2.00	.468	.364	Log <sub>10</sub>
Chlorophyll <i>a</i> ( μg/L)	165	.858	.845	.503	2.40	0.00	.053	-.220	Log <sub>10</sub>
DO (mg/L)	236	6.95	7.20	1.59	10.9	1.40	-.765	.624	None
Temperature (C)	235	27.9	28.2	1.93	31.6	22.7	-.459	-.248	None
Secchi (meters)	236	.052	.041	.214	.580	-.699	-.201	-.276	Log <sub>10</sub>
TSS (mg/L)	226	.674	.699	.377	2.11	0.00	.318	.762	Log <sub>10</sub>
Turbidity (NTU)	223	.638	.602	.337	1.46	0.00	.335	-.650	Log <sub>10</sub>
Data Set Sample Size	236								

The summary statistics are provided using the transformed data.

**Table 31: Summary Statistics, Missingness, and Transformations for Select Water Quality Variables in the Piedmont Ecoregion**

Photic Variable and Units	N	Mean	Median	Standard Deviation	Maximum	Minimum	Skewness	Kurtosis	Transformation
TP (mg/L)	3656	-1.41	-1.32	.381	-.013	-2.00	.101	-.604	Log <sub>10</sub>
PO <sub>4</sub> (mg/L)	1913	-1.83	-2.00	.353	-.268	-2.00	2.14	3.98	Log <sub>10</sub>
TN (mg/L)	3655	-3.12	-.292	.261	1.20	-1.70	.043	1.79	Log <sub>10</sub>
TON (mg/L)	3644	-.458	-.420	.259	.748	-2.00	-.845	2.76	Log <sub>10</sub>
TIN (mg/L)	3656	-1.16	-1.22	.587	1.01	-2.00	.400	-.639	Log <sub>10</sub>
Chlorophyll <i>a</i> ( $\mu\text{g/L}$ )	2513	1.17	1.49	.456	2.56	0.00	-.292	.073	Log <sub>10</sub>
DO (mg/L)	3658	8.55	8.30	1.96	2.72	.900	1.56	1.11	None
Temperature (C)	3666	25.6	27.7	6.13	38.4	3.00	-1.83	2.98	None
Secchi (meters)	3680	-.054	-.046	-.290	.954	-1.00	-1.01	5.37	Log <sub>10</sub>
TSS (mg/L)	3495	.819	.845	..388	2.48	0.00	.105	.379	Log <sub>10</sub>
Turbidity (NTU)	2188	.677	.633	.360	2.48	0.00	.670	.805	Log <sub>10</sub>
Data Set Sample Size	3694								

The summary statistics are provided using the transformed data.

**Table 32: Summary Statistics, Missingness, and Transformations for Select Water Quality Variables in the Middle Atlantic Coastal Plain Ecoregion**

Photic Variable and Units	N	Mean	Median	Standard Deviation	Maximum	Minimum	Skewness	Kurtosis	Transformation
TP (mg/L)	424	-1.61	-1.70	.412	-.056	-2.00	1.07	.600	Log <sub>10</sub>
PO <sub>4</sub> (mg/L)	124	-1.99	-2.00	.068	-1.52	-2.00	5.13	26.4	Log <sub>10</sub>
TN (mg/L)	425	-.418	-.387	.347	.869	-1.22	.059	.442	Log <sub>10</sub>
TON (mg/L)	426	-1.04	-1.05	.058	-.174	-1.05	14.6	212	Log <sub>10</sub>
TIN (mg/L)	425	-1.26	-1.30	.439	.810	-2.00	.587	1.01	Log <sub>10</sub>
Chlorophyll <i>a</i> ( $\mu\text{g/L}$ )	343	.555	.477	.500	2.38	0.00	.744	.135	Log <sub>10</sub>
DO (mg/L)	423	7.18	7.40	1.53	14.3	.300	-.905	5.44	None
Temperature (C)	426	28.0	28.4	2.75	37.0	17.5	-1.36	3.46	None
Secchi (meters)	422	-.038	.000	.337	.491	-1.00	-.493	-.303	Log <sub>10</sub>
TSS (mg/L)	391	.585	.477	.499	2.52	0.00	.922	.827	Log <sub>10</sub>
Turbidity (NTU)	378	.512	.477	.436	2.30	-.398	.727	.363	Log <sub>10</sub>
Data Set Sample Size	426								

The summary statistics are provided using the transformed data.

**Table 33: Correlations of Select Water Quality Variables in Blue Ridge Ecoregion**

	TP	PO <sub>4</sub>	TN	TON	TIN	Chl. <i>a</i>	DO	Temp.	Secchi	TSS	Turb.
TP	1	.755	.628	.529	.442	.546	.219	-.035	-.590	.530	.591
PO <sub>4</sub>	.755	1	.547	.438	.396	.594	.081	-.032	-.336	.273	.346
TN	.628	.547	1	.443	.900	.479	.169	-.028	-.408	.282	.310
TON	.529	.438	.443	1	.008	.633	.240	.168	-.550	.250	.271
TIN	.442	.396	.900	-0.209	1	.225	.071	-.112	-.187	.192	.214
Chl <i>a</i>	.546	.594	.479	.633	.225	1	.243	.154	-.443	.059	.140
DO	.219	.081	.169	.240	.071	.243	1	.061	-.316	.038	.003
Temp.	-.035	-.032	-.028	.168	-.112	.154	.061	1	-.231	-.122	-.049
Secchi	-.590	-.336	-.408	-.550	-.187	-.443	-.316	-.231	1	-.314	-.348
TSS	.531	.273	.282	.250	.192	.059	.038	-.122	-.314	1	.791
Turb.	.591	.346	.310	.271	.214	.140	.003	-.049	-.348	.791	1

Note: Missing data handed using listwise deletion

**Table 34: Correlations of Select Water Quality Variables in Piedmont Ecoregion**

	TP	PO <sub>4</sub>	TN	TON	TIN	Chl. <i>a</i>	DO	Temp.	Secchi	TSS	Turb.
TP	1	.631	.485	.348	.362	.452	.070	-.057	-.380	.530	.375
PO <sub>4</sub>	.631	1	.249	.135	.258	.214	.085	-.014	-.150	.151	.096
TN	.485	.249	1	.859	.507	.338	-.102	-.187	-.421	.368	.289
TON	.348	.135	.859	1	-.006	.371	.031	-.070	-.359	.253	.112
TIN	.362	.258	.507	-.006	1	.035	-.251	-.247	-.218	.351	.376
Chl <i>a</i>	.452	.214	.338	.371	.035	1	.176	-.136	-.401	.223	.101
DO	.070	.085	-.102	.031	-.251	.176	1	-.100	-.099	-.028	-.025
Temp.	-.057	-.014	-.187	-.070	-.247	-.136	-.100	1	.230	-.126	-.080
Secchi	-.380	-.150	-.421	-.359	-.218	-.401	-.099	.230	1	-.334	-.238
TSS	.530	.151	.398	.253	.351	.223	-.028	-.126	-.334	1	.794
Turb.	.375	.096	.289	.112	.376	.101	-.025	-.080	-.238	.794	1

Note: Missing data handed using listwise deletion.

**Table 35: Correlations of Select Water Quality Variables in Southeastern Plain Ecoregion**

	TP	PO <sub>4</sub>	TN	TON	TIN	Chl. <i>a</i>	DO	Temp.	Secchi	TSS	Turb.
TP	1	.675	.738	.710	.330	.472	.172	-.208	-.189	.787	.437
PO <sub>4</sub>	.675	1	.853	.847	.203	.117	.154	-.153	-.241	.764	.376
TN	.738	.853	1	.990	.257	.200	.119	-.104	-.300	.925	.525
TON	.710	.847	.990	1	.116	.228	.117	-.053	-.296	.913	.509
TIN	.330	.203	.257	.116	1	-.157	.037	-.365	-.083	.255	.204
Chl <i>a</i>	.472	.117	.200	.228	-.157	1	-.076	-.084	-.470	.461	.449
DO	.172	.154	.118	.117	.037	-.076	1	-.024	-.008	.121	.161
Temp.	-.208	-.153	-.104	-.053	-.365	-.084	-.024	1	.068	-.113	.072
Secchi	-.189	-.241	-.300	-.296	-.083	-.470	-.008	.068	1	-.433	-.589
TSS	.787	.764	.925	.913	.255	.461	.121	-.113	-.433	1	.647
Turb.	.437	.376	.525	.509	.204	.449	.161	.072	-.589	.647	1

Note: Missing data handed using listwise deletion

**Table 36: Correlations of Select Water Quality Variables in Middle Atlantic Coastal Plain Ecoregion**

	TP	PO <sub>4</sub>	TN	TON	TIN	Chl. <i>a</i>	DO	Temp.	Secchi	TSS	Turb.
TP	1	.738	.849	.852	.482	.410	-.335	-.156	-.437	.776	.854
PO <sub>4</sub>	.738	1	.583	.573	.442	.060	.055	-.046	-.195	.666	.769
TN	.849	.583	1	.996	.634	.260	-.215	-.087	-.556	.840	.845
TON	.852	.573	.996	1	.562	.277	-.220	-.092	-.555	.837	.835
TIN	.482	.442	.634	.562	1	.006	-.082	-.012	-.339	.540	.595
Chl <i>a</i>	.410	.060	.260	.277	.006	1	-.378	-.285	-.186	.071	.194
DO	-.335	.055	-.215	-.220	-.082	-.378	1	.155	.479	-.010	-.027
Temp.	-.156	-.046	-.087	-.092	-.012	-.285	.155	1	-.055	.013	-.104
Secchi	-.437	-.195	-.556	-.555	-.339	-.186	.479	-.055	1	-.348	-.359
TSS	.777	.666	.840	.837	.540	.071	-.010	.013	-.348	1	.864
Turb.	.854	.769	.845	.835	.595	.194	-.027	-.104	-.359	.864	1

Note: Missing data handed using listwise deletion

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# Biography

## Background

Date of Birth: November 22, 1979

Place of Birth: Harrisonburg, VA

## Education

Duke University, Nicholas School of the Environment and Earth Sciences,  
Durham, NC. Ph.D. in Water Quality Modeling and Decision Analysis. December 2007.

University of Virginia, Charlottesville, VA. B.A. with Distinction in  
Environmental Sciences. May 2002.

## Publications

1. **Kenney, M.A.**, R.T. Clemen, and K.H. Reckhow. (in preparation) Choosing Water Quality Impairment Criteria: Using science and judgments to inform decision-making. Decision Analysis.

2. **Kenney, M.A.**, K.H. Reckhow, G.B. Arhonditsis, and R.T. Clemen. (in preparation) Use of Predictive Models to Select Nutrient Criteria Variables for North Carolina Lakes and Reservoirs. Journal of American Water Resources Association.

3. **Kenney, M.A.**, G.B. Arhonditsis, L.C. Reiter, M. Barkley, and K.H. Reckhow. (in review) Selection of Nutrient Criteria Variables using the Predictive Approach for the Kissimmee Chain-of-Lakes in Florida using Structural Equation Modeling. Lake and Reservoir Management.

4. Sutton-Grier, A.E, **M.A. Kenney**, C.J. Richardson. (submitted) Does restoration of ecosystem structure restore ecosystem function? A cross-system comparison of soil condition controls of denitrification potential in restored wetlands using structural equation modeling. *Restoration Ecology*.
5. **Kenney, M.A.** (2007) Making the Most of your Teaching Assistantship (TA) Experience. *Frontiers in Ecology and the Environment*. 8(5): 445-446.
6. **Kenney, M.A.** (2007) Which Nutrient Criteria Should States and Tribes Choose to Determine Water Body Impairment? Using Science and Judgment to Inform Decision-Making. National Water Research Institute, First Annual Graduate Fellowship Research Conference Proceedings. pp. 1-6.
7. **Kenney, M.A.** and M.A. White. (2007) A Benefit-Cost Model for Evaluating Remediation Alternatives at Superfund Sites Incorporating the Value of Ecosystem Services. *Reclaiming the Land: Rethinking Superfund Institutions, Methods, and Practices*. G. Macey and J. Cannon, eds. pp. 169-196.
8. **Kenney, M.A.**, K.H. Reckhow, and G.B. Arhonditsis (2007) Evaluating Eutrophication-Related Water Quality Parameters in North Carolina Lakes and Reservoirs. North Carolina Department of Environment and Natural Resources, Division of Water Quality. Report. pp. 102.
9. Arhonditsis, G.B., C.A. Stow, L.J. Steinberg, **M.A. Kenney**, R.C. Lathrop, S.J. McBride, and K.H. Reckhow. (2006) Exploring Ecological Patterns with Structural Equation Modeling and Bayesian Analysis. *Ecological Modelling*. 192: 385-409.
10. Reckhow, K.H., G.B. Arhonditsis, **M.A. Kenney**, S. J. McBride, R.J. Gosnell, C.A. Stow, and H.W. Paerl. (2006) Water Quality Indicators: Nutrient Impacts on Chlorophyll or Algae Species Composition. Water Environment Research Federation. Report 02-ECO-1. pp. 79.
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12. Sutton-Grier, A.E. and **M.A. Kenney**. (2005) Recruiters and Academia: A Class Act. *Nature*. 436: 886.

13. **Kenney, M.A.** (2003) Development of Teaching Assistant Support Materials and Training Workshop for the Nicholas School of the Environment and Earth Sciences. Duke University Center for Teaching, Learning, and Writing. Report. pp. 4.

14. **Kenney, M.A.** (2002) Development of a Value-Based Model to Provide Options for Reuse of Superfund Sites. University of Virginia Department of Environmental Sciences Distinguished Majors Program Thesis.

### **Awards, Honors, and Scholarships / Fellowships**

- National Water Resources Institute Fellowship (\$15,000; 2006-2007)
- National Science Foundation FORWARD (Focus on Reaching Women for Academics, Research, and Development) to Professorship. (\$350; 2007)
- Sigma Xi, The Scientific Research Society (Full member; 2005 – present)
  - President, Duke University Chapter of Sigma Xi (2005 – 2007)
  - National Committee on Nominations (2006 – 2009)
- North American Lake Management Society (NALMS) Conference Scholarship (\$800; 2006)
- Decision Analysis Society, Institute for Operations Research & the Management Sciences (INFORMS) Conference Scholarship (\$200; 2006)
- Duke University, Graduate School Conference Scholarship (\$1000; 2006, 2007)
- Duke University, Nicholas School of the Environment and Earth Sciences Conference Scholarship (\$900; 2005, 2006, 2007)

- Center for Teaching Learning and Writing Fellow (\$2000; 2003 – 2004)
- Preparing Future Faculty, Fellow (2003 – 2004)
- Honorable Mention in National Science Foundation Graduate Research

Fellowship (2004)