A Predictive Approach to Nutrient Criteria

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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 violations 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 the U.S. EPA. We acquired data sets for four case studies (Lake Washington, Neuse River Estuary, San Francisco Bay, and Lake Mendota) 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.

Introduction

The U.S. Environmental Protection Agency recently recommended an ecoregion-based national strategy for establishing nutrient criteria, following a multiyear study of needs and approaches (*1*). 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 overenrichment are a leading cause of surface water impairment (*2*). 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; the EPA'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, violation of the criteria is a basis for regulatory enforcement, which typically requires establishment of a 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 on the basis of societal values, which should reflect the realities of society's tradeoffs between environmental protection and cost (*3*). 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) (*4*, *5*) to data from 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) (*6*, *7*). 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 reformulate 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 EPA, 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

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a discussion comparing strategies for nutrient criteria selection and a list of modifications for improving our approach.

Background

Designated uses evolved from the goals of the Clean Water Act. As part of the water quality standard for a regulated water body, 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 (*8*). 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 (*9*), 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 (*10*). Thus, the 40 μg/L criterion developed from an ad hoc process of science-based expert judgment.

The current U.S. EPA approach for nutrient criteria development is a similar mix of science and expert-judgment. In 1998, the President's Clean Water Action Plan directed the EPA to develop a national strategy for establishing nutrient criteria. The resultant multiyear study produced a set of documents (*1*) 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 unimpacted 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? EPA guidance (*11*) 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 EPA 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 (*10*) 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 EPA 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 the EPA, 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 to 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 (*6*, *7*, *12*)

(a) to reexpress designated use in terms of measured water body conditions,

(b) to formulate a conceptual model of the variables that affect the designated use, and

(c) to 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 water body, 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.

Methods—Expert Elicitation and Structural Equation Modeling

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.

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 (*13*). 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 a Michaelis—Menten phytoplankton growth model with multiplicative nitrogen and phosphorus 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 1970s strategy involving scientific consensus was heavily judgmental. And, while drawing upon objective statistical analyses, the proposed EPA 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 (*6*, *7*, *12*) 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 (*14*—*16*). 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 on the basis of suggestions from the expert elicitation literature (*6*, *7*, *12*, *17*). 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 ensure 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, they could remove themselves from participation in the interview.

Given willingness to participate, we contacted each expert via e-mail and provided him with a description of the project and the reason his judgment was necessary. Additionally, the e-mail 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 water body. 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 water body. 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 on the basis of 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 (*6*, *7*). To additionally minimize human error due to heuristics, we conducted a consistency check on the response variable value provided by the expert to ensure consistency within their responses and that the experts were not anchoring their responses on the current state standard (*6*, *12*). 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.

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 (*4*, *5*, *18*, *19*), but ecological applications are still relatively limited and even less common in aquatic ecosystems (*20*—*22*). 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 (*4*, *5*) (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 (*21*). 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 preconceptualizations 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

$$H_o\colon \ \sum = \sum(\theta)$$

where $\sum$ is the population (or sample) covariance matrix of observed variables, θ is a vector that contains the model parameters, and $\sum(\theta)$ is the model-implied covariance matrix (*4*). 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 compaired with all other models containing the same exogenous and endogenous variables (nested analysis) (*4*).

Case Studies

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 (*23*). 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, and *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 (*23*, *24*). Lake Washington serves as prime habitat for juvenile salmon and supports both recreational activities and local fisheries (*25*). Washington State submitted a proposed policy for nutrient criteria in 2003, pending approval by the U.S. EPA 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 (*26*).

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 (*27*). 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 (*26*), 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 multivariate 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 71% 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 nonsignificant) path between total phosphorus and chlorophyll *a* represents a phenomenon that 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 judgment 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 that 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).

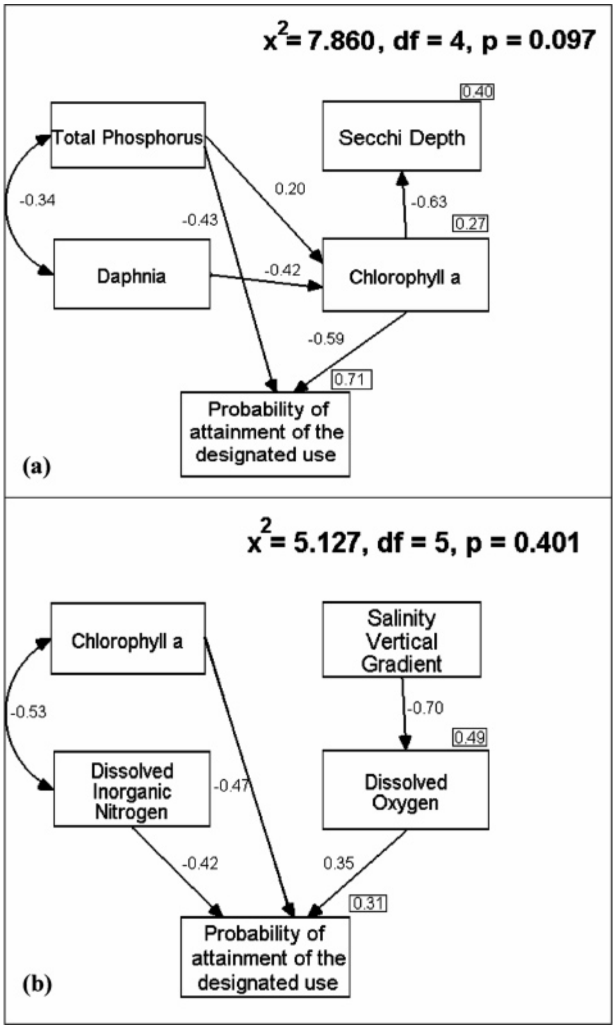

FIGURE 1. Structural equation models for (a) Lake Washington and (b) the Neuse River estuary. The numbers correspond to the standardized path coefficients and the R^2 values (numbers in rectangles); χ^2, df, and *p* correspond to the chi-squared test values, the degrees of freedom, and the probability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

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 (*28*). The Neuse has also been listed as an impaired water body 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 nonpoint source inputs of nitrogen, though developing evidence suggests that phosphorus may sometimes contribute to excessive algal levels (*29, 30*). 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 (*31*). 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.

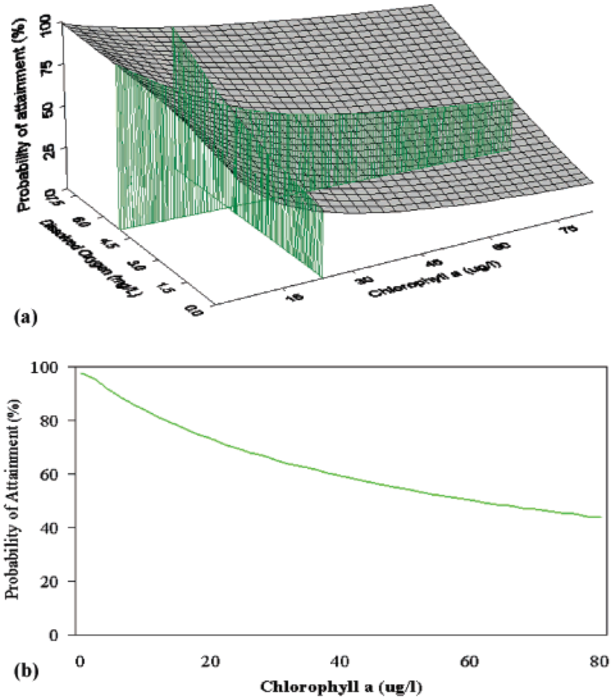

FIGURE 2. Application of the Neuse River Estuary SEM for estimating the probability of attainment of the designated use (logit transformation of the expert's response) for the entire summer range of dissolved oxygen and chlorophyll *a* levels in the Neuse River estuary (Figure 2a). The two green surfaces correspond to specific levels of the two candidate criteria, i.e., dissolved oxygen = 5 mg/L and chlorophyll *a* = 20 μg/L (the latter is also shown in Figure 2b).

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 (*32*). 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. On the basis of 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.

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 ensuring 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.

(1) The primary change is to consult multiple experts and to employ proper procedures to combine expert judgments (*5*, *33*); a single expert was convenient for this initial analysis, but criteria choice can be expected to be more robust when multiple experts are involved.

(2) An appealing alternative is to conduct a user survey that is undertaken concurrent with water quality sampling. 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.

(3) 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 U.S. EPA 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 the predictive approach presented here can address this critical need.

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