Group Decision and Negotiation **10**: 355–373, 2001

Stakeholder Values and Scientific Modeling in the Neuse River Watershed

MARK BORSUK, ROBERT CLEMEN, LYNN MAGUIRE, AND KENNETH RECKHOW
Duke University, Durham, NC 27708

Abstract

In 1998, the North Carolina Legislature mandated a 30% reduction in the nitrogen loading in the Neuse River in an attempt to reduce undesirable environmental conditions in the lower river and estuary. Although sophisticated scientific models of the Neuse estuary exist, there is currently no study directly relating the nitrogen-reduction policy to the concerns of the estuarine system's stakeholders. Much of the difficulty lies in the fact that existing scientific models have biophysical outcome variables, such as dissolved oxygen, that are typically not directly meaningful to the public. In addition, stakeholders have concerns related to economics, modeling, implementation, and fairness that go beyond ecological outcomes. We describe a decision-analytic approach to modeling the Neuse River nutrient-management problem, focusing on linking scientific assessments to stakeholder objectives. The first step in the approach is elicitation and analysis of stakeholder concerns. The second step is construction of a probabilistic model that relates proposed management actions to attributes of interest to stakeholders. We discuss how the model can then be used by local decision makers as a tool for adaptive management of the Neuse River system. This discussion relates adaptive management to the notion of expected value of information and indicates a need for a comprehensive monitoring program to accompany implementation of the model. We conclude by acknowledging that a scientific model cannot appropriately address all the stakeholder concerns elicited, and we discuss how the remaining concerns may otherwise be considered in the policy process.

Key words: Bayes net, decision analysis, predictive modeling, probability network, risk assessment, stakeholder involvement, value-focused thinking

1. Introduction

Coastal areas provide tremendous ecological, economic, and recreational benefits. However, they are also especially vulnerable to pollution because of high population growth rates and intense land uses. The United States 1998 Clean Water Action Plan highlights coastal eutrophication (the presence of a dense nutrient-stimulated algal population, the decomposition of which can kill animal life through oxygen deprivation) as being one of the most serious water quality problems currently faced by the United States (USEPA 1998). The report emphasizes that, in order to be successful, future efforts to restore and protect coastal waters must be based on both sound science and active public involvement.

The Neuse River estuary in North Carolina (figure 1) is a typical example of a stressed coastal system. The estuary is experiencing characteristic symptoms of nutrient overload, including excessive algal blooms, low levels of dissolved oxygen, massive fish kills, and outbreaks of toxic microorganisms (Burkholder et al. 1993; Paerl et al. 1995). These problems have generally been attributed to recent land-use changes in the watershed. Population expansion and development are occurring rapidly throughout the basin, and the region is home to a growing commercial hog-farming industry.

In response to public concern over aquatic habitat degradation and human health implications, the North Carolina legislature recently mandated a 30% reduction in nitrogen load. While a load reduction of this magnitude may lessen problems related to eutrophication, the degree of improvement and the overall impacts on the estuary and its biota are unknown. In particular, it is not known how a 30% reduction will affect qualities of the estuary that are important to stakeholders. In other words, is 30% the "right" number?

One effort to answer this question has been to develop a deterministic water-quality model (CE-Qual-W2) for the Neuse estuary (Bowen 1997). The CE-Qual-W2 model is process-based; predictions are based on equations of mass, momentum, and energy balance. The outcome variables for the model focus on dissolved oxygen concentrations, phytoplankton biomass, and concentrations of chlorophyll a, variables that have relatively little meaning to the general public and policy makers. Instead, stakeholders and decision makers are more interested in events such as large algal blooms, fish kills, and human health impacts. As a result, policy makers are left with the difficult task of extrapolating model endpoints to attribute variables that matter to stakeholders, even though this task might be better addressed by scientists more familiar with the natural system.

Although the CE-Qual-W2 model is described as being of intermediate complexity relative to other eutrophication models, it simulates a large number of processes and operates on a small time step. This level of complexity leads to another concern: High levels of complexity generally make even a reduced uncertainty analysis difficult to perform, and a full consideration of uncertainty may be impossible. Without information on the likelihood of various possible outcomes, decision makers cannot use the powerful tools of decision analysis and may make less than optimal decisions (Morgan and Henrion 1990). Also, without adequate uncertainty analysis, prioritization of additional research intended to reduce model uncertainty cannot occur, further reducing the model's utility for management. Even if the required assessments could be obtained, Reckhow (1994) has argued that propagation of individual parameter uncertainty and measurement error through the complex mechanistic model may result in an elevated level of uncertainty in final predictions. Reckhow recommends instead modeling the system at a more aggregate level of detail, using a decision-analytic approach that is designed to incorporate uncertainty from the start. By doing so, and by including outcome variables that are meaningful to stakeholders, scientists can provide much more useful decision support to policy makers faced with difficult decisions that must be made under conditions of uncertainty.

This paper describes an ongoing project in which we use a decision-analytic approach to model the Neuse River estuary and promote communication between scientists and stakeholders. The effort began with a series of stakeholder discussions to identify their concerns with the estuarine system. This process is described in Section 2. These discussions were essential not only for the model-building process, but also to give stakeholders a voice, thereby facilitating the development of stakeholder trust in the policy-implementation process (Lind 1995; Lind and Tyler 1988). Following the identification of stakeholder concerns, we initiated construction of a probability-network model to link attributes corresponding to stakeholder interests with proposed management actions. A description of the current model is found in Section 3. Once the model is completed and validated with existing data, it can be used to provide scientific guidance for water-quality management decisions, as described in Section 4. By following a process of adaptive management, or "learning-by-doing," the model can be updated as scientists gather new information based on the response of the ecological system to initial policy implementation. Section 5 concludes with a discussion of the implications and limitations of our study.

2. Eliciting stakeholder concerns

2.1. Elicitation methodology

The first step in our effort was to study the interests of stakeholders who care about the health of the Neuse estuary, with the aim of identifying measurable variables (attributes) that are meaningful to them and to their elected officials. We identified 240 potential stakeholders from a variety of sources, including a list of National Pollutant Discharge Elimination System permit holders, literature searches, attendance records from previous Neuse-related meetings, and word of mouth. We also solicited names from extension and rural-development agents in an effort to include segments of the public who do not ordinarily participate in public meetings or respond to mailings. We sent introductory packets to these individuals introducing them to our project and soliciting their input through phone or personal interview, extended written survey, and/or attendance at a public meeting. We also enclosed a brief introductory questionnaire (see Appendix) to obtain baseline data on attitudes toward Neuse management processes.

We received 55 responses to our initial written survey and 27 responses to a later, more extensive survey. We supplemented these with 23 telephone interviews, which followed essentially the same format as the extended written survey.

We also held four public meetings at cities in North Carolina: two in Goldsboro, one in New Bern, and one in Raleigh. These meetings drew a total of 29 participants. In each case, the discussions were directed to generate a list of interests and concerns related to nutrient management in the Neuse River system. At the end of each public meeting, a short survey was distributed to solicit input about the stakeholder-involvement process and about whether the respondents felt their views had been heard. After each meeting, detailed notes were organized, and the compiled list of identified interests was sent to the participants for corrections or additions.

Finally, we conducted nine in-depth, personal interviews with selected stakeholders. Each such interview took from one to two hours, giving us the opportunity to talk at length, probing the individual's concerns. The interviewees spanned a wide variety of interests and perspectives, including the owner of a seafood restaurant; an elderly, lifelong resident of a small town in eastern North Carolina; a fishing guide; a corporate attorney; and a group of summer-camp employees.

2.2. Elicitation results

The combined results of our data-collection efforts are summarized in Tables 1 and 2. These tables show the different types of stakeholder concerns. Table 1 displays the fundamental objectives for the estuary and associated resources, the public-involvement process, and the restoration process. Table 2 displays the means objectives for the estuarine system and resources, the public-involvement process, and the scientific modeling effort. Following Keeney (1992), fundamental objectives are the issues and subissues that stakeholders genuinely care about, and means objectives are ways to accomplish the fundamental objectives.

By design, much of the stakeholder discussion revolved around water quality. Many stakeholders saw a high level of water quality as the key fundamental objective, while others felt it was important at least in part as a means to maintaining and expanding fish and shellfish populations. In addition, however, stakeholders recognized other roles that water quality plays. For example, stakeholders interested in waterfront property indicated that the odor of the estuary has an impact on values; thus, improving the odor of the water would be a means to increasing overall property values. Clear water is also valued because it hearkens back to earlier times when the estuary was healthier; some stakeholders yearn for "how it used to be" in the estuary, with clear water and sandy bottoms.

Table 1. Fundamental objectives of Neuse River Stakeholders

Estuarine system and resources	Public involvement process	Restoration process
Ecosystem • Water quality (e.g., fish, shellfish, species abundance, O_2, cleanliness, odor, clarity, sandy bottom, no algal blooms, no human-caused fishkills) • Fish stocks • Recreational fishing • Aquatic biodiversity • Undisturbed ecosystem Human activities • Healthy economy Economic development Tourism Commercial fishery High property values • Desirable place to live • Navigable waters • Pleasant recreation • Aesthetics Human health • Safe recreation • Edible shellfish and fish	• Two-way exchange between public and decision makers • Repeated participation by public in analysis and decision making • Improved public access to, and appreciation of, the river (e.g., volunteer water-quality and biota sampling) • Evidence that citizen input and participation is used (e.g., via newsletters) • Reduced conflict among interested parties	• Efficiency of nutrient reduction efforts (i.e., actions taken are most likely to have positive effect, provide the most clean-up for money spent) • Fairness of allocation of financial responsibility for cleanup Based on accurate understanding of contribution of various sources (point, non-point, atmospheric) Based on effectiveness of control Low burden on parties (point sources) that have already made substantial efforts Low burden on small farmers and small businesses • Acceptance of personal responsibility Absence of "finger pointing" Action taken without waiting for exact proof of amount of impact • Level of cleanup balanced with cost • Low cost • Commitment from upstream and downstream parties • Straightforward implementation and enforcement

Table 2. Means objectives of Neuse River Stakeholders

Estuarine system and resources	Public involvement process	Scientific modeling process
Ecosystem • Control hypoxia • Control sediment to tributaries (to protect benthic communities, mollusks) • Control water quantity (timing of peak flows)	• Provide public education (reasonable expectations for clean-up, personal responsibility for pollution) • Include river health indexes (e.g., O_2) on weather report • Have the governor deliver an "ecological address" on the state of North Carolina's environment	Model characteristics • Comprehensive • Appropriate spatial resolution • Differential effects of different types buffers • Cumulative effects • Nonlinear relationships • Historical data
Human activities • Control growth upstream through urban planning • Charge impact fees to offset water-quality impacts of development where possible • Minimize impervious surfaces • Preserve green space • Encourage public transportation • Control overfishing • Permit nutrient trading	• Motivate participation in cleanup	• Credible (endorsed by academics at various institutions) Model capabilities • Compare outputs for different management plans under comparable hydrologic scenarios • Make output available in a timely fashion for management action • Predict duration and magnitude of hypoxia • Support an adaptive-management approach

Our stakeholder study clearly shows that stakeholders care about more than just the river and estuary health. They care about how they are involved in the process, especially knowing that their participation matters and is actually used. They also care about the efficiency, effectiveness, and fairness of any restoration efforts. Some of these can be thought of as both means objectives and fundamental objectives. For example, "two-way communication" could be thought of as a means for stakeholders to communicate their concerns and thereby to better accomplish their objectives. We list "two-way communication" as a fundamental objective, though, representing stakeholders' interest in being taken seriously. In fact, social science research shows that process objectives can be important both as means to achieving other substantive objectives (e.g., Thibaut and Walker (1975, 1978) argue that procedural concerns stem from anticipated effects on substantive outcomes) and as ends in themselves (e.g., work by Lind (1995) and Lind and Tyler (1988) shows that participants value fair procedures for their symbolic value, above and beyond anticipated effects on outcome).

In addition to process concerns, stakeholders articulated concerns about the model to be used to support restoration decisions. Their sophistication regarding modeling issues was a pleasant surprise, despite their somewhat daunting demands; they wish the model to be timely, inclusive, and fully endorsed by the academic community!

All of the stakeholders' process and modeling concerns are valid objectives, but most fall beyond the scope of the current scientific modeling effort, the focus of which is to predict the impact of proposed nutrient-management strategies on the water-quality attributes of concern to the public. To the extent feasible, stakeholders' concerns with regard to process have been and continue to be considered as the model is developed and implemented. The current project, though, has the funding and political mandate only to study the biophysical characteristics of the Neuse River system. A far broader effort, including ongoing interaction among scientists, modelers, stakeholders, and decision makers, would be required in order to address all the concerns of the public and stakeholders.

To better understand the public's definition of estuarine health, we solicited more detailed biophysical concerns and suggestions for ways to measure these attributes. These are summarized in Table 3 and include water-quality measures such as water clarity, taste, lack of odor, levels of chlorophyll a and dissolved oxygen, and presence or absence of algal toxins. Biological quality indicators include algae levels and presence of excessive, submerged aquatic vegetation, as well as abundance, diversity, and health of fish and shellfish. Human health concerns included the presence of fecal coliform and toxic microorganisms including *Pfiesteria piscicida*.

A more complete documentation of the stakeholder study, including extensive discussion of the results as well as copies of all survey instruments, can be found in Maloney, Maguire, and Lind (2000).

3. A probability-network model of the Neuse Estuary

3.1. Modeling methodology

With a solid understanding of stakeholder concerns, we are in a position to develop a model that appropriately links these concerns to the proposed nutrient loading changes. Because of the complexity of the natural system and the need for a model to support decisions in the near term despite scientific uncertainty, we rely on a probabilistic model known as a probability network (Reckhow 1999).

Probability networks are graphical models that depict probabilistic relationships among uncertain variables. In the graph, nodes represent variables, and an arc from one node to another represents a relationship between the corresponding variables. A node that has no incoming arcs is said to have no predecessors, and such a variable can be described probabilistically by a marginal (or unconditional) probability distribution. A node that has incoming arcs, and hence has predecessors in the graph, depends probabilistically on its predecessors and hence is described by a set of conditional probability distributions, one for each possible combination of values for its predecessors. No connecting arc between any two cells implies conditional independence between the variables.

The probability network constitutes an integrated description of the probabilistic relationships among the system's variables and can be used to perform both prediction and inference. These models are sometimes referred to as "Bayes Nets," emphasizing the fact that, given observed values for any of the variables, probability distributions conditioned on those observations can be inferred for the other variables using Bayes theorem. Developed by researchers in artificial intelligence (who often use the term "belief network") (Pearl 1988), decision analysis (where the term "influence diagram" is common) (Oliver and Smith 1990), and statistics (where "Bayes Net" is often used) (Lauritzen and Spiegelhalter 1988), probability networks are only beginning to be applied by environmental modelers. Applications to date include severe weather forecasting (Abramson et al. 1996), fisheries management (Varis 1995), climate change prediction (Kuikka and Varis 1997), and water quality modeling (Reckhow 1999). However, to our knowledge no previous work has integrated probability networks with a stakeholder-involvement process.

The network's conditional probability distributions may be developed in a number of ways. Relatively simple process-based models can be used, along with a full uncertainty analysis, to relate the variables. As discussed above, however, this may be impractical for complex models with many parameters. An alternative is to use historical data to quantify the relationships using statistical methods. In many policy-making situations, such as the Neuse management case, insufficient data may be available to estimate all relationships in the network, and gathering the required data in a timely manner may be infeasible. Therefore, probability-network modelers often rely on expert opinion, eliciting the conditional distributions using standard protocols such as those described in Morgan and Henrion (1990) or Meyer and Booker (1991). We use expert judgment to create parts of the Neuse model; a description of the elicitation and modeling process is given below.

3.2. Model description

Our probability-network model of estuarine response is shown in figure 2. Based on a comprehensive survey of the relevant scientific literature as well as a series of meetings with university researchers, the model describes estuarine response to changes in nitrogen and phosphorus loading. Spatially, the model relates to the portion of the estuary from New Bern, NC, to the bend near Minnesott Beach (see figure 1). Temporally, the model depicts one year, concentrating on the summer season. The model focuses on biophysical measures from Table 3. Specifically, predictive endpoints (shown as hexagons in figure 2) include water clarity, the number of severe algal blooms, the probability of a major fish kill in the summer season, human health impacts related to the toxic microorganism *Pfiesteria piscicida*, reduction in shellfish habitat, and long-term fish health. Although a detailed description of the model is beyond the scope of this paper, a brief description follows. Additional details are available from the authors.

The current scientific belief is that nitrogen loading from both point and non-point sources in the Neuse watershed stimulates excessive algal productivity in the estuary (Paerl et al. 1998). Together with other dissolved and suspended matter, this algal growth reduces water clarity. In addition, enhanced algal production may lead to severe bloom events under calm, non-mixing wind conditions. Suspended algae eventually die and sink to the sediment surface where they are consumed by bacteria. This process consumes oxygen in the lower water column leading to low-oxygen, or "hypoxic," conditions. Such conditions reduce the availability of habitat for shellfish, an important stakeholder concern. Many researchers also believe that fish kills are caused primarily by this low-oxygen bottom water combined with wind conditions that force the bottom water to the surface, trapping fish along the shore where they suffocate (Paerl et al. 1998). In addition, toxic *Pfiesteria* may play a significant role in fish kills both by directly attacking the fish and by making them more susceptible to harsh conditions (Burkholder et al. 1999).

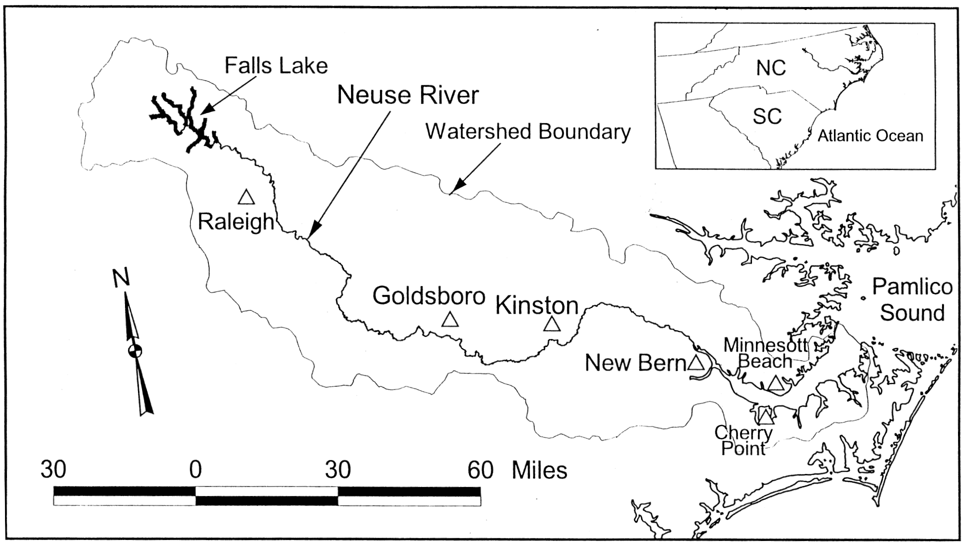

Figure 1. The Neuse River Estuary.

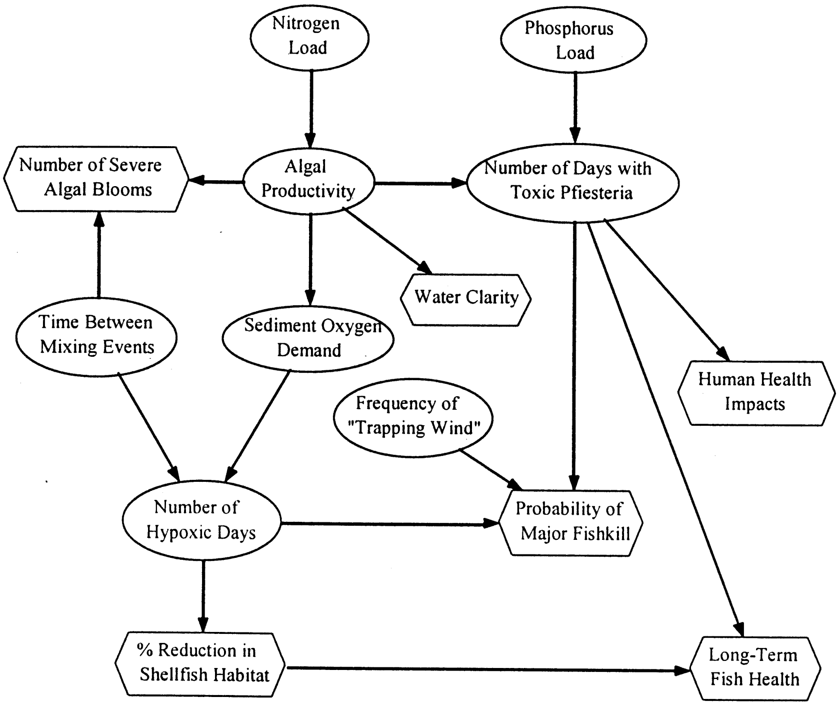

Figure 2. A graphical model of Estuarine response.

The presence of active *Pfiesteria* in the estuary is believed to be linked to estuarine productivity in general. Additionally, phosphorus loading may exert a stimulatory effect on *Pfiesteria* (Burkholder and Glasgow 1997). In addition to killing fish, both *Pfiesteria* and hypoxia compromise long-term fish health by weakening fish, reducing reproduction, and affecting food resources. *Pfiesteria* has also been found to adversely impact human health by causing respiratory and neurological distress in laboratory researchers and fishermen (Glasgow et al. 1995). However, the seriousness of this threat to the general public is controversial (Griffith 1999), and research related to the human health effects of *Pfiesteria* is still in its early stages. The limited understanding of *Pfiesteria's* role means that some of the relationships in our model are highly uncertain and may be modified as the model is adapted in the future.

To formalize the graphical model, each variable must be defined precisely. This ensures that probability assessments obtained from different sources will be compatible and that the definitions of the variables are not inadvertently modified in the course of model development. Defining the metrics for each variable with appropriate precision is often no small task, requiring compromises among level of detail, degree of uncertainty, ease of elicitation, and occasionally differing expert views on the most appropriate measure. Table 4 summarizes the metrics chosen for each variable in the estuary model. The table also includes information on the source of the conditional or marginal probabilities.

Table 3. Stakeholder's biophysical concerns and proposed measures for the Neuse Estuary

Concerns	Proposed measures
Water quality	Clarity
	Taste, odor
	Chlorophyll a
	Dissolved Oxygen (O_2)
	Algal toxins
Biological quality	
Plant	Algae levels
	Submerged aquatic vegetation (intermediate levels optimal)
Animal	
Fish	Abundance
	Diversity
	Fish kills
	Lesions
	Size of harvest
Shellfish (edible)	Abundance
	Distribution
Human health	
Fecal coliform bacteria	
Other pathogenic microorganisms (e.g., *Pfiesteria*)	

Table 4. Definition of model variables and endpoints

Variable name	Metric	Information source for probability model
Nitrogen load	Total annual nitrogen load to the estuary as calculated following the method of Stow et al. 1999 (in metric tons).	Data, expert judgment, and/or nutrient-loading model
Phosphorus load	Total phosphorus load as calculated following the method of Stow et al., 1999 (in metric tons).	Data, expert judgment, and/or nutrient-loading model
Algal productivity	Depth integrated, spatially averaged, annual productivity as estimated using biweekly measurements (gC/m^2).	Data
Number of days with toxic *Pfiesteria*	Presence of *Pfiesteria piscicida* in a toxic stage at concentrations greater than 300 cells/ml during the summer season (days/season).	Limited data, expert judgment
Time between mixing events	Number of days between vertical mixing events during the summer season.	Data, expert judgment
Frequency of "Trapping Winds"	Average frequency of winds sufficient to force the bottom water to the surface.	Data, expert judgment
Sediment oxygen demand	Daily average amount of oxygen consumed in sediments ($gO_2/m^2/d$).	Data, process-based model
Number of hypoxic days	Total number of days in summer season with average oxygen concentrations below 2.0 mg/l (days/season).	Data, process-based model
Number of severe algal blooms	Number of days with chlorophyll a levels greater than 40 mg/l at selected sampling stations (days/season).	Data, expert judgment
Water clarity	Average Secchi disk depth at select locations of recreational importance to public (meters).	Data, expert judgment
Human health impacts	Qualitative risk of target population expressing neurological or respiratory symptoms.	Expert judgment
Probability of major fish kill	Likelihood of a fish kill with greater than 10,000 dead fish in the middle estuary.	Expert judgment
% Reduction in shellfish habitat	Percentage of area and number of days in summer season in which oxygen levels are considered to be creating conditions uninhabitable by shellfish.	Expert judgment
Long-term fish health	Descriptive indicator of long-term health of the resident fish population.	Expert judgment

3.3. Model construction

Our probability-network model of the Neuse estuary is currently implemented in Analytica (Decisioneering 1997). Although the model is still in development, we describe below the construction of the probability distributions and typical results that the model can provide to support management decisions.

Consider, for example, the variable "Time Between Mixing Events." As shown in figure 2, this is a marginal uncertainty node; its value does not depend on the values of other variables. We used expert judgment to develop the probability distribution for this node, using Morgan and Henrion's (1990) elicitation technique to interview a physical oceanographer familiar with circulation and transport, flow profiles, and wind measurements in the Neuse estuary. The elicitation method used a series of questions to establish points on the cumulative distribution function (CDF) representing the number of days between mixing events.

The assessment of subjective probabilities can be subject to cognitive biases (Kahneman, Slovic, and Tversky 1982). We used Morgan and Henrion's *fixed value* approach in a frequency context in order to minimize such biases (Anderson 1998). For example, a typical question was, "If you were to observe 100 vertical mixing events, how many do you think would be less than *x* days apart?" An exponential distribution with a rate parameter (equal to the average time between mixing events) of 7 days fits the assessments very closely. This result is consistent with a theoretical model in which extreme wind and flow conditions are assumed to be the mechanisms of vertical mixing such that the occurrence of mixing events follow a Poisson process (Devore 1991).

As an example of how to develop a conditional distribution for the probability network, Borsuk et al. (1999) describe a relatively simple process-based model through which "Number of Hypoxic Days" is related to "Time Between Mixing Events" and "Sediment Oxygen Demand." This model separately accounts for the competing factors of oxygen consumption and physical reoxygenation, including the effects of temperature and vertical stratification. In its simplified form, the model can be represented by the differential equation,

$$\frac{dC}{dt} = -k_d C + k_v (C_s - C), \qquad (1)$$

where C is the estuarine bottom water oxygen concentration, t is the time since the last mixing event, k_d is a temperature-dependent first-order rate constant of sediment oxygen demand, k_v is the rate constant of reoxygenation from the surface layer, and C_s is the oxygen concentration in the surface layer. The model captures the notion that the change in C depends on the balance between oxygen consumption in the sediment and reoxygenation from the surface layer. Equation (1) has the analytic solution

$$C = \frac{C_s \left[p(k_v + k_d) + k_v \left\{\exp\left((k_v + k_d)t\right) - 1\right\}\right]}{(k_v + k_d)\exp\left((k_v + k_d)t\right)}, \qquad (2)$$

where p is the initial value of the oxygen concentration in the bottom water (at $t = 0$) expressed as an unknown percent, 100p, of C_s.

Parameters k_v, k_d, and p were estimated using historical data and a least-squares optimization procedure. This approach naturally incorporates both parameter uncertainty and a stochastic error term, thereby representing a probabilistic relationship among the variables. This relationship can then be used to generate probabilistic predictions of hypoxia, conditional on various values for its predecessors. For example, if we assume that the sediment oxygen demand is reduced by 25% (as might be determined by values of its own predecessors) and the distribution of time between mixing events remains the same (as elicited in the procedure described above), a distribution of the predicted number of days of hypoxia can be generated which includes the effects of uncertainty. Figure 3 shows this conditional distribution compared with the base-case scenario of no change in sediment oxygen demand.

3.4. Model validation

For a probability network, model validation is accomplished by using the model to "predict" past observations. To do this, historic data on marginal, or input, variables are used to generate probabilistic predictions of endpoints, which are then compared with observed responses. If the comparison is unsatisfactory, refining the model structure or probabilities may be necessary. Sensitivity analysis can help determine which variables drive the model outputs, thus providing further guidance in refining the structure of the model. When the model can be shown to accurately reproduce past observations (in a probabilistic sense), it can be used as described below to evaluate the effect of proposed nutrient-control measures.

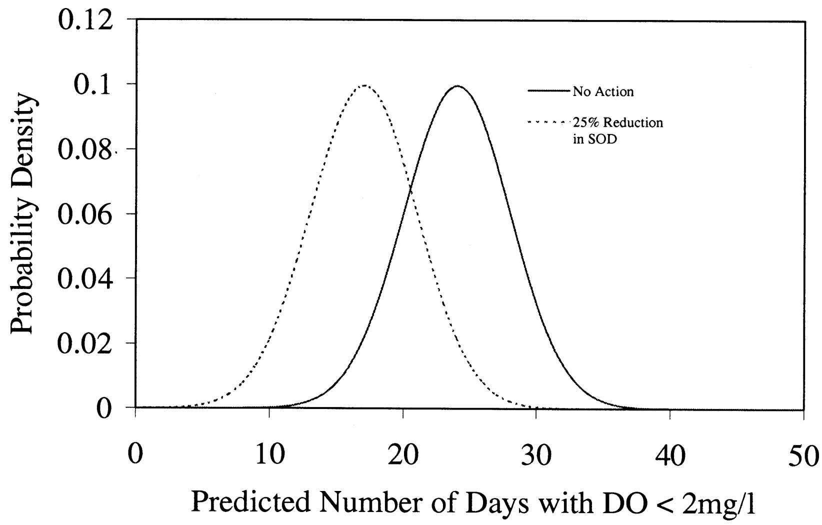

Figure 3. Conditional risk profiles for number of hypoxic days. The dashed line shows the conditional distribution for hypoxic days assuming a reduction in sediment oxygen demand of 25%. The solid line represents the base-case scenario.

4. Model use for management and decision-making

With the model fully specified and validated, we can produce probability distributions (or "risk profiles") for model endpoints, given particular sets of conditioning values. For example, in order to test the currently proposed management action, we might fix the value for nitrogen loading at 30% less than its present value or use a probability distribution representing attainment of an uncertain level of reduction around 30%. We can then assess the resulting change in the conditional values of model endpoints.

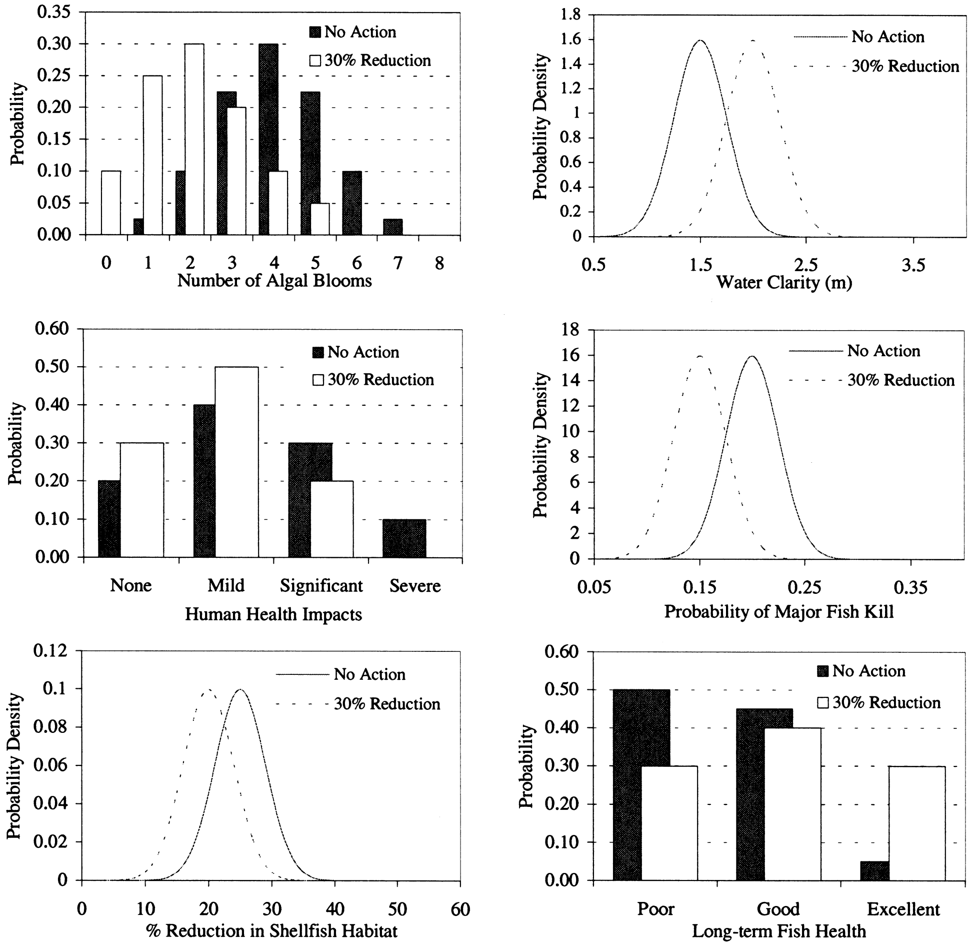

Figure 4. Hypothetical risk profiles for model endpoints. The two management plans compared in this hypothetical scenario are the base case, in which no action is taken, versus a goal of reducing the nutrient load by 30%.

Analytica uses Monte Carlo simulation to perform these calculations, resulting in outputs in the form of risk profiles for the endpoints along with descriptive statistics (e.g., expected value standard deviation, percentiles) of the simulation results. Figure 4 shows two hypothetical risk profiles for each of the endpoint variables. For each variable, one risk profile corresponds to "No Action" and the other to a fixed 30% reduction in nitrogen loading. (We emphasize that these results are hypothetical and meant only to demonstrate the *form* of the model output. They are *not* actual quantitative predictions.) A decision maker can visually compare the probabilistic profiles to assess the nature of the risks associated with candidate management actions. In the hypothetical case in figure 4, all of the risk profiles show a beneficial effect (in a probabilistic sense) resulting from the 30% reduction.

The comparison of multiple management plans can be facilitated by considering summary statistics, such as means, medians, or exceedance probabilities. Alternatively, the risk profiles can be analyzed for stochastic dominance (Clemen 1996), allowing for rejection of clearly inferior (i.e., dominated) alternatives. Finally, because the risks relate directly to endpoint variables that are meaningful to stakeholders, they can be evaluated in terms of associated costs and benefits or by means of a multiattribute utility function to yield expected utilities.

It is not currently common practice for multiattribute probability-network models to be used to support water-quality management decisions. Instead, whether it is the initial intent or not, successful management often involves an ad-hoc series of judgment-based decisions, followed by implementation, feedback, and readjustment. This "learning by doing" approach seems to be a pragmatic attempt to deal with growth, change, new information, and imprecise forecasting. Walters (1986) labels this strategy "adaptive management" and emphasizes that it is a continual process. Rather than creating an elaborate model *a priori* and basing all subsequent decisions on predictions from that model, the adaptive approach emphasizes updating of the model based on observation and learning as time passes. The probability-network approach facilitates model updating as new information is gained. In turn, management actions can adapt based on results from the updated model. This approach is particularly appealing in environmental applications where population growth, land use change, and variability in climatic forcing functions exceed the limited realm of current observation and experience. Natural systems involve complex and often highly nonlinear relationships among various elements; deterministic prediction in these chaotic environments can be difficult in the short term and useless in the long term. The probabilistic approach represented by the network model is more suitable in general for complex natural systems of concern to environmental managers.

The potential value of adaptive management is related to the notion of expected value of information (EVI) (Raiffa and Schlaifer 1961). A primary determinant of EVI is the relative difference between the current state of knowledge and how much can be learned through scientific study. For example, suppose the current state of knowledge about the hydrologic dynamics of a watershed is such that scientists are unable to determine which of a set of management policies is preferred. Now imagine a set of scientific studies that would permit the choice of a management action; the more diagnostic a scientific study and the more a decision maker can tailor management policy to the specific conditions found in the watershed, the more valuable that study would be. Furthermore, the ability to adapt through time also adds value; the more the decision maker has the flexibility to modify the policy as knowledge is gained, the greater the EVI.

The concept of EVI also suggests that policy implementation must include a well-designed monitoring program to provide the data necessary to identify and understand changes in the estuary as they occur. A monitoring program should measure changes in key variables in the model, including biophysical variables such as dissolved oxygen, chlorophyll a, and phytoplankton biomass, as well as model output variables such as fish kills, algal blooms, shellfish habitat, and others. The probabilistic nature of the network model makes it possible to evaluate the sensitivity of model predictions to this new information in order to prioritize research needs. For example, the current extent of toxic *Pfiesteria* is not well known and hence would be represented in the network model by a relatively broad probability distribution. Sensitivity analysis with the probabilistic model can indicate whether the uncertainty in this variable has a substantial effect on model predictions. If it does, and if its EVI is sufficiently high, then further research on this variable and its relationship with others may be identified as a priority.

In the Neuse River, there is a particularly compelling reason to consider adaptive management and EVI calculations. As the 30% nitrogen-reduction plan is implemented over time, a well-designed water-quality monitoring program can provide information about the actual (not model-projected) system response to management actions and to changing conditions that are not under management control. This information can be used to update the model as needed, and decision makers can in turn use the updated model to assess the effectiveness of new management plans.

We may appear to be optimistic in our expectations for how our model will be used by policy makers in North Carolina to guide management of the Neuse watershed. As model builders, we naturally hope that our efforts will have a meaningful impact on the decision-making process, but we are far from naïve in this regard. While we are encouraged by the fact that our model is part of a legislatively mandated program of research on the Neuse, we recognize that our model is but one of several sources of information that will be consulted by decision makers in their effort to obtain insight and guidance. In addition, decision makers will be subject to political pressures from many stakeholder groups that may interfere with their reliance on scientific analysis. Ultimately, those decision makers must chose as wisely as they can, given the information they have and the nature of the political situation. By linking specific stakeholder interests to scientific understanding of the ecological system and by providing an appropriate tool for adaptive management, our model will become, we hope, an important source of information and insight for those who must ultimately choose and implement a sound management plan for the Neuse River watershed.

5. Conclusion

We have described a decision-analysis approach to the management of water quality for the Neuse River and estuary. The process flows naturally from the identification of stakeholder values to the construction of a model that is sensitive to those values, validation of the model, and finally to the use of the model to support both management and research decisions. The model is conceived of as a dynamic tool that can grow and improve as additional data are collected through a program of adaptive management.

Our stakeholder study and analysis bears discussion in two respects. First, as we mentioned in Section 3, some of the objectives can be viewed as fundamental objectives, means objectives, or both. The most appropriate representation depends in part on the particular decision context (Keeney 1992). Even with a particular context in mind, such as management of nutrient loading in the Neuse River, stakeholder concerns may not be easy to categorize. Refinement of objectives may be possible via further stakeholder discussion. Even with such iterations, however, eventually the analyst must exercise some judgment in the interpretation and representation of stakeholder preferences. It should not be surprising that one arrangement of means and ends objectives might be appropriate for a largely biophysical modeling effort, and another arrangement of the same objectives might be most appropriate for a largely socioeconomic modeling effort.

The second point of discussion relates to the breadth of concerns that our stakeholders expressed. As mentioned, they are vocal not only about characteristics of the estuary itself, but also about the decision-making process (and their role in it), characteristics of the model, and the nature of the cleanup process. It is clear that the modeling and monitoring efforts that we describe address only a part of the stakeholder concerns. A more comprehensive program is needed to ensure that stakeholders' concerns regarding public participation, efficiency and effectiveness of cleanup efforts, and fair allocations of cleanup responsibility are met. For example, it may be necessary to develop a more complete model of nutrient contribution for sources throughout the Neuse River basin in order to assess the effectiveness, efficiency, and fairness of specific management plans. Stakeholder meetings and newsletters may be used to inform stakeholders about the modeling and restoration efforts and to ensure that their ongoing concerns and input are heard and included in the overall effort. Although we acknowledge that all projects must be bounded for reasons of time, budget, and current knowledge, we hope that the current project can continue to incorporate as many of the stakeholder interests as possible. In addition, we hope that the results from our stakeholder study can help persuade policy makers of the importance of addressing more than just scientific concerns in future environmental projects.

Acknowledgements

We wish to thank the editor and referees for comments that improved the paper. This research has been supported in part by the UNC Water Resources Research Institute of North Carolina.

Appendix

Introductory survey sent to stakeholders

What is the nature of your connection with the Neuse River? *Please check all that apply*:

_____ Local Resident
_____ Farmer
_____ Recreationist (fisher, boater, etc.)
_____ Discharge permittee
_____ Ecologist or environmentalist
_____ Other (specify: ________________)

Have you been active in the debate about the Neuse River on behalf of an organized group?
_____ Yes (name of group: ____)
_____ No

If yes, has your participation been: _____ part of your job OR _____ outside your job

Have you participated in other decision-making processes influencing the Neuse River in the past?
_____ Yes (please answer follow-up question) _____ No (please answer follow-up question)

If yes, in what ways have you participated? *On the blank beside each choice, please indicate the approximate number of times you have done each*:

_____ Attended public meetings
_____ Talked to the media
_____ Other (specify:____)
_____ Completed surveys
_____ Been interviewed by phone

If no, why not?

_____ Not interested
_____ Didn't know how to get involved
_____ Not enough time
_____ Other

Of those you've participated in, which formats have you found most satisfying? Why?
____
____
____

Which formats have you found least satisfying? Why?
____
____
____

Please circle one of the numbers below to indicate how much you agree with the following statements

Strongly Disagree <————————> Strongly Agree
1 2 3 4 5

I feel the State has tried to identify citizens' concerns about the Neuse River.
1 2 3 4 5

I am satisfied with the amount my voice has been heard on this issue.
1 2 3 4 5

All the right people have been involved in making decisions about the Neuse.
1 2 3 4 5

Please list any people or groups you feel have been excluded from the process in the past:

Who else should we add to our list of contacts for this process?

Please use this space for any additional comments you have:

References

Abramson, B., J. Brown, W. Edwards, A. Murphy, and R. L. Winkler. (1996). “Hailfinder: A Bayesian System for Forecasting Severe Weather,” *International Journal of Forecasting* 12, 57–71.

Anderson, J. L. (1998). “Embracing Uncertainty: The Interface of Bayesian Statistics and Cognitive Psychology,” *Conservation Ecology*, 2, 2.

Borsuk, M. E., C. A. Stow, R. A. Luettich Jr., H. W. Paerl, and J. L. Pinckney. (1999). “Probabilistic Prediction of Hypoxia in the Neuse River Estuary Using an Empirical Model of Oxygen Dynamics,” *Limnology and Oceanography*. Under review.

Bowen, J. D. (1997). “Using a Mechanistic Eutrophication Model for Water Quality Management of the Neuse River,” University of North Carolina-Charlotte, draft.

Burkholder, J. M., H. B. Glasgow, and E. J. Noga. (1993). “The Role of a Newly Discovered Toxic Dinoflagellate in Finfish and Shellfish Kills in the Neuse and Pamlico Estuaries,” *Albemarle-Pamlico Estuarine Study Report* 93-08, NC. Department of Environment, Health and Natural Resources, Raleigh, NC.

Burkholder, J. M., and H. B. Glasgow. (1997). “*Pfiesteria Piscicida* and Other *Pfiesteria*-like Dinoflagellates: Behavior, Impacts, and Environmental Controls,” *Limnology and Oceanography* 42, 1052–1075.

Burkholder, J. M., M. A. Mallin, and H. B. Glasgow. (1999). “Fish Kills, Bottom-Water Hypoxia, and the Toxic *Pfiesteria* Complex in the Neuse River and Estuary,” *Marine Ecology Progress Series* 179, 301–310.

Clemen, R. T. (1996). *Making Hard Decisions: An Introduction to Decision Analysis*, 2nd edn. Pacific Grove, CA.: Duxbury.

Decisioneering. (1997). Analytica. Denver, CO.: Decisioneering, Inc.

Devore, J. L. (1991). *Probability and Statistics for Engineering and the Sciences*. Pacific Grove, CA.: Brooks/Cole.

Glasgow, H. B., J. M. Burkholder, D. E. Schmechel, P. A. Tester, and P. A. Rublee. (1995). “Insidious Effects of a Toxic Estuarine Dinoflagellate on Fish Survival and Human Health,” *Journal of Toxicology and Environmental Health* 46, 501–522.

Griffith, D. (1999). “Exaggerating Environmental Health Risk: The Case of the Toxic Dinoflagellate *Pfiesteria*,” *Human Organization* 58, 119–127.

Kahneman, D., P. Slovic, and A. Tversky. (1982). *Judgment under Uncertainty: Heuristics and Biases*. Cambridge: Cambridge University Press.

Keeney, R. L. (1992). *Value-Focused Thinking*. Cambridge, MA.: Harvard University Press.

Kuikka, S., and O. Varis. (1997). “Uncertainties of Climatic Change Impacts in Finnish Watersheds: A Bayesian Network Analysis of Expert Knowledge,” *Boreal Environment Research* 2: 109–128.

Lauritzen, S. L., and D. J. Spiegelhalter. (1988). “Local Computations with Probabilities on Graphical Structures and their Application to Expert Systems (with discussion),” *Journal of the Royal Statistical Society* B50, 157–224.

Lind, E. A. (1995). *Social Conflict and Social Justice: Some Lessons from the Social Psychology of Justice*. Leiden, the Netherlands: Leiden University Press.

Lind, E. A., and T. R. Tyler. (1988). *Social Psychology of Procedural Justice*. New York: Plenum.

Maloney, K. A., L. A. Maguire, and E. A. Lind. (2000). "Neuse River Estuary Modeling and Monitoring Project Stage 1: Assessment of Stakeholder Interest and Concerns to Inform Long-term Modeling," UNC Water Resources Research Institute Report No. 325-G, Raleigh, NC.

Meyer, M., and J. Booker. (1991). *Eliciting and Analyzing Expert Judgment: A Practical Guide*. London: Academic Press.

Morgan, M.G., and M. Henrion. (1990). *Uncertainty*. Cambridge: Cambridge University Press.

Oliver, R. M., and J. Q. Smith (eds). (1990). *Influence Diagrams, Belief Nets, and Decision Analysis*. Chichester: Wiley.

Paerl, H. W., M. A. Mallin, C. A. Donahue, M. Go, and B. L. Peierls. (1995). "Nitrogen Loading Sources and Eutrophication of the Neuse River Estuary, North Carolina." Report No. 291. UNC Water Resources Research Institute, Raleigh, NC.

Paerl, H. W., J. L. Pinckney, J. M. Fear, and B. L. Peierls. (1998). "Ecosystem Responses to Internal and Watershed Organic Matter Loading: Consequences for Hypoxia in the Eutrophying Neuse River Estuary, North Carolina, USA," *Marine Ecology Progress Series* 166, 17–25.

Pearl, J. (1988). *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference*. San Mateo, CA: Morgan Kaufmann.

Raiffa, H., and R. Schlaifer. (1961). *Applied Statistical Decision Theory*. Cambridge, MA: Harvard University Press.

Reckhow, K. H. (1994). "Water Quality Simulation Modeling and Uncertainty Analysis for Risk Assessment and Decision Making," *Ecological Modeling* 72, 1–20.

Reckhow, K. H. (1999). "Water Quality Prediction and Probability Network Models," *Canadian Journal of Fisheries and Aquatic Sciences* 56, 1150–1158.

Stow, C. A., M. E. Borsuk, and D. W. Stanley. (1999). "Nutrient Loading in the Neuse River Watershed: An Opportunity for Adaptive Management," Duke University, draft.

Thibaut, J. and L. Walker. (1975). *Procedural Justice: A Psychological Analysis*. Hillsdale, NJ: Erlbaum.

Thibaut, J., and L. Walker. (1978). "A Theory of Procedure," *California Law Review* 66, 541–566.

USEPA. (1998). *Clean Water Action Plan: Restoring and Protecting America's Waters*. EPA-840-R-98-001.

Varis, O. (1995). "Belief Networks for Modelling and Assessment of Environmental Change," *Environmetrics* 6, 439–444.

Walters, C. J. (1986). *Adaptive Management of Renewable Resources*. New York: McMillan.