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Cyanobacterial Harmful Algal Blooms: Chapter 38: Integrating Human and Ecological Risk Assessment: Application to the Cyanobacterial Harmful Algal Bloom Problem

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Chapter 38: Integrating human and ecological risk assessment: application to the cyanobacterial harmful algal bloom problem

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Abstract

Environmental and public health policy continues to evolve in response to new and complex social, economic and environmental drivers. Globalization and centralization of commerce, evolving patterns of land use (e.g., urbanization, deforestation), and technological advances in such areas as manufacturing and development of genetically modified foods have created new and complex classes of stressors and risks (e.g., climate change, emergent and opportunist disease, sprawl, genomic change). In recognition of these changes, environmental risk assessment and its use are changing from stressor-endpoint specific assessments used in command and control types of decisions to an integrated approach for application in community-based decisions. As a result, the process of risk assessment and supporting risk analyses are evolving to characterize the human-environment relationship. Integrating risk paradigms combine the process of risk estimation for humans, biota, and natural resources into one assessment to improve the information used in environmental decisions (Suter et al. 2003b). A benefit to this approach includes a broader, system-wide evaluation that considers the interacting effects of stressors on humans and the environment, as well the interactions between these entities. To improve our understanding of the linkages within complex systems, risk assessors will need to rely on a suite of techniques for conducting rigorous analyses characterizing the exposure and effects relationships between stressors and biological receptors. Many of the analytical techniques routinely employed are narrowly focused and unable to address the complexities of an integrated assessment. In this paper, we describe an approach to integrated risk assessment, and discuss qualitative community modeling and Probabilistic Relational Modeling techniques that address these limitations and evaluate their potential for use in an integrated risk assessment of cyanobacteria.

Introduction

Cyanobacterial blooms occur in both fresh water and marine environments, producing a variety of toxins, and posing risks to humans and animals through recreational and drinking water use as well as consumption of contaminated fish and shellfish (Codd et al. 2005). As a result of their complex ecology, involving multiple endpoints we propose an integrative approach in assessing the risks posed by cyanobacterial blooms.

The environmental risk assessment paradigm is shifting from independent analyses of human health or ecological effects to a more integrative, or unified, approach. The idea of integrating risk assessment has been the topic of extensive discussion over the past decade (e.g., Harvey et al. 1995; WHO 2000). Integration ideally combines the process of risk estimation for humans, biota, and natural resources into one assessment to improve the information used in environmental decisions, resulting in more effective protection of both humans and the environment (Suter et al. 2003b). A benefit to this approach is a broader, system-level evaluation that considers the interactions of the effects of stressors on humans and the environment, as well the interactions between these entities. In addition, stressors other than chemicals need to be considered. The basis for such an integrated approach would be the perspective that ecosystems serve as part of the foundation defining human well-being and vice versa.

Risk assessments are important tools for informing public health and environmental protection decisions. They constitute the scientific reasoning for estimating the likelihood of an adverse human or ecological effect resulting from exposure to a stressor. Although the human health and ecological risk assessment paradigms were developed independently, they are related (Suter et al. 2003a). In both paradigms, risk characterization is a key step providing a description of the evidence concerning the hazard, potential exposures, and the uncertainties, variability, and assumptions used in the assessment. Thus, the integration of risk assessment approaches is encapsulated in the analytical processes it entails.

The shift in risk assessment to an integrated approach is consistent with changes in the scientific approach to complex problems. In many instances, a multidisciplinary approach is a necessity to evaluate cause and effects relationships fully. Wilson (Wilson 1998) noted that science is no longer a specialized activity, but involves the synthesis of causal explanations. Thus, scientific research is shifting towards understanding linkages within highly complex systems (Vitousek et al. 1997; Wilson, 1998; NAS, 2000; Forget and Lebel, 2001).

To improve our understanding of the linkages of complex systems as part of an integrated risk assessment, risk assessors must rely on a suite of techniques for conducting rigorous analyses characterizing exposure and effects relationships among stressors and biological receptors. Current analytical techniques have been criticized as inadequate and irrelevant; they can be misinterpreted due to a lack of understanding of the problem and the inability to deal with uncertainty (NRC 1996; Peterman and Anderson 1999). Further, many of the commonly used techniques are narrow in focus and unable to evaluate complex systems adequately. In this paper, we describe integrated risk assessment and review community-level modeling techniques that account for current limitations. Lastly, we evaluate their potential for integrated risk assessment of the cyanobacterial harmful algal bloom (CHAB) problem.

Integrated Risk Assessment Paradigms

Over the past decade, several frameworks for integrating risk have been proposed that are based on existing approaches for human health and ecological risk assessments. Some approaches view integration in the context of chemical exposures, combining acute and chronic risks to organisms and considering exposures from different sources, pathways and routes (Gurjar and Mohan 2003; Bridges and Bridges 2004). Harvey and coworkers (Harvey et al. 1995) developed a 'holistic' approach that consisted of concurrent *and* integrated health and ecological assessments. Their process followed the steps originally outlined by the NAS (NAS 1983) conducting human health and ecological assessments in parallel. A series of risk choices is produced for the risk manager by integrating the results of two parallel assessments during the risk characterization step. Using mercury as a case study, they developed a risk characterization consisting of a series of risk estimates for humans exposed through inhalation or ingestion that address neurological and reproductive effects, and for wildlife exposed through the aquatic food chain addressing reproductive success and decreased species distribution. The authors suggested that the series of risk estimates would provide options for risk managers to choose from in making a decision (Harvey et al. 1995). Although cast as a holistic process, the Harvey et al. (Harvey et al. 1995) approach is not really integrative, but rather a comparison of different risk values generated for different exposure scenarios and toxicity endpoints; protective of different species. Thus, this approach may be too generic and unresponsive to a particular problem or management decision.

A special forum of the World Health Organization's International Programme on Chemical Safety (IPCS) developed another approach (Munns et al. 2003). They outlined an integrated process combining elements of both human health and ecological processes (WHO 2001; Suter et al. 2003b). This paradigm (Figure 1) is more closely aligned with the concepts of the *Guidelines for Ecological Risk Assessment* (USEPA 1998). Here, hazard identification becomes an element of problem formulation, and dose response assessment occurs as part of the effects characterization. Most importantly, this approach considers the interactions among stressors and receptors such as wildlife or humans, and the abiotic environment.

One distinct difference of the IPCS integrated approach from the Harvey et al. (Harvey et al. 1995), NAS (NAS 1983) and ecological risk paradigms (USEPA 1998) is the involvement of stakeholders and risk managers in the process. The human health and ecological risk paradigms were designed to be independent from risk management so that their outcomes reflect scientific analyses that are not influenced by socio-political bias. In the IPCS approach, stakeholder and risk management involvement throughout the process is viewed as essential to ensure buy-in and responsiveness of the assessment to the specific problem, considering both human and ecological risks where applicable (Suter et al. 2003b). While this, in and of itself, does not ensure integration, it increases the potential depending on how the problem is defined at the onset of the risk assessment.

The IPCS approach combines the process of risk estimation for humans, biota, and natural resources into one assessment for the purpose of improving the information used in environmental decisions, resulting in more effective protection of resources valued by society (Miranda et al. 2002; Suter et al. 2003b). Integration is achieved through all phases of the risk assessment process (Suter et al. 2003b). Under problem formulation, integration entails the development of stressor-driven assessment questions common to both health and environmental problems that focus on potential susceptible human and ecological endpoints. Exposure and effects characterizations are integrated through an evaluation of all the possible sources of exposure and an understanding of common modes of toxic action in humans and other organisms. Similar to the holistic approach (Harvey et al. 1995), the IPCS risk characterization includes multiple estimates of risk from which a best estimate of human and ecological risk is selected using a common and consistent approach (Suter et al. 2003b). The authors go on to indicate that evidence for health and ecological risks would be integrated when appropriate but do not describe how this would be achieved.

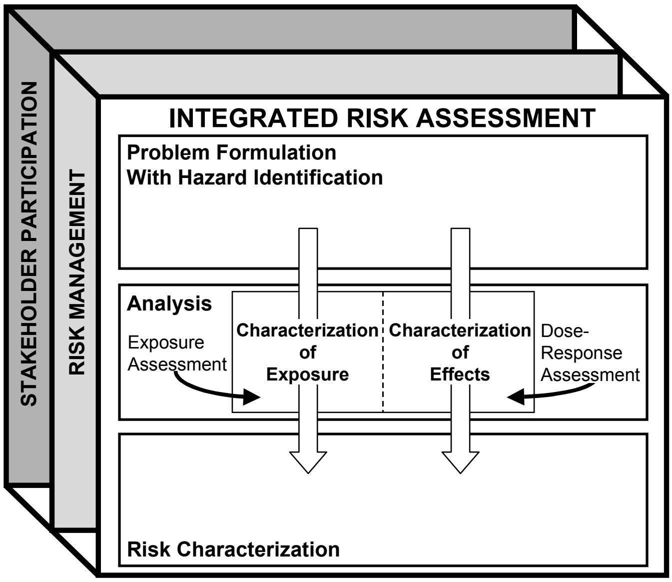

Fig. 1 Integrated Risk Assessment Paradigm. Adapted from WHO 2001.

The IPCS integrated approach was applied to several complex environmental problems (Table 1). The case studies developed using the integrated approach identify aspects of where integration can or should occur with respect to exposure and effects characterization, but they do not actually conduct integrated assessments. Rather, they illustrate how such assessments might be conducted. The risk characterization section in each of the case studies largely reflects parallel risk comparisons. Two studies (Ross and Birnbaum 2003; Vermeire et al. 2003) propose a common quantitative approach, a Toxic Equivalency Factor (TEF) approach as a means of integrating risks. It is not clear, however, that having a common quantitative approach to estimate risks for different species is actually integrative, but rather reflects the commonalities in the toxic endpoints and mechanisms of toxicity for the exposures and species of interest. Thus, the IPCS approach goes beyond Harvey et al.'s (Harvey et al. 1995) holistic approach in describing levels of integration throughout the risk assessment process. However, the information included in the risk characterization step largely presents parallel risk estimates for human and ecological endpoints under different exposure and effect scenarios. The responsiveness of the assessment to a particular problem is likely to be greater under the IPCS approach given the interaction with risk managers and stakeholders throughout the process.

Other approaches to integrative assessments have been proposed that focus on human and environmental linkages including socioeconomic and political factors (e.g., Bruins and Heberling 2005; Stahl et al. in press), or have focused more broadly on human health-ecological integrity reflecting dimensions of both the natural and social systems (Miranda et al. 2002). Epstein (Epstein 1994) developed an integrated assessment framework of climate change and ecosystem vulnerability. His generalized framework depicted overlapping and interacting climate and social systems with ecosystems whose intersection directly or indirectly produced various outcomes ranging from changes in health, crop yields, and demography to economic productivity. Epstein noted that integration was dependent on the use of specific biological, social or geochemical indicators depicting the functions of complex systems. Referring to the complex relationship between disease emergence and changes in climate and ecosystems, Epstein (Epstein 1994) proposed a number of principles for modeling and monitoring complex ecosystems. He emphasized the need to account not only for direct impacts to the different systems but also those indirect effects resulting from the interactions among factors within the three overlapping systems. He noted that those diseases transmitted directly from person to person reflect changes in population density with little interaction among the three systems, while vector-borne diseases reflect environmental changes involving all three systems in his integrated model. Integration in Epstein's approach also occurs through scientific and political collaborations. He did not present an overall assessment of risk but suggested guidelines for identifying system vulnerabilities affecting overall stability and resilience; key elements in his view for mitigating disease emergence.

Table 1 Summary of IPCS integrated risk assessment case studies.

Environmental Problem	Assessment Endpoints	Areas of Integration	Proposed Risk Characterization	Reference
“Dioxin-like” Persistent Organic Pollutants	Humans and upper trophic level wildlife	·Route of exposure ·Mode of action ·Toxicity	Apply Toxic Equivalency Approach (TEF) to both humans and wildlife	Ross and Birnbaum 2003.
Tributyl- and triphenyltins	Humans and piscivorous wildlife	·Route of exposure ·Mode of action ·Toxicity	Species and exposure-specific human and ecological risk estimates	Sekizawa et al. 2003.
UV-Radiation	Amphibians, coral, humans, and oceanic primary productivity	·Exposure pathways ·Mechanistic pathways	Parallel characterization of risk across assessment endpoints.	Hansen et al. 2003.
Organophospherous pesticides	Humans and wildlife	·Exposure pathways ·Toxicity	Species-specific TEFs	Vermeire et al. 2003.
Nonylphenol	Humans (occupational and environmental exposure), wildlife, and aquatic organisms	·Exposure pathways ·Mechansim of action ·Toxicity	Species and exposure-specific human and excological risk estimates	Bontje et al. 2004

Vanleewen et al. (Vanleewen et al. 1999) presented a conceptual 'butterfly' model that focuses on human health in an ecosystem context. Human health is determined from the intersection of biophysical socioeconomic environments. The boundaries of the butterfly could be at the community, watershed, or population level and include the interactions between humans and the nonhuman environment. Their model is not an approach for assessing risk *per se* but can be viewed as a mechanism for determining risk factors influencing human health. As the authors noted, this model focuses only on human health and does not determine health for other species in the ecosystem, limiting its utility for comprehensive assessment of risk.

Integrative Analytical Approaches to Risk Assessment

The integrated paradigms described above provide frameworks for considering human and environmental interactions but fall short of demonstrating specific analytical techniques for conducting an integrated risk analysis. The examples include a mix of conceptual, integrated approaches that are either descriptive or consist of parallel risk assessments. Considering the models presented by Epstein (Epstein 1994) and VanLeeuwen et al. (VanLeeuwen et al. 1999), it is clear that an evaluation of interactions among human populations, their environment, and other important ecological factors are needed in conducting an integrated analysis. This type of evaluation is similar to that encompassed by an ecoepidemiological approach. Similar to human epidemiology, ecoepidemiology has been used to study the ecological effects that are prevalent in certain areas among population groups, communities and ecosystems and their potential causes (Bro-Rasmussen and Løkke 1984; Martens 1998). This approach focuses on a description of the effects, identification of causes, and understanding their linkages. Humans are considered as part of the environment in these analyses.

An ecoepidemiological approach is similar to community and systems-level ecological risk assessment with respect to understanding relationships between biotic and abiotic factors. Levins (Levins 1973) noted that addressing more complex systems required breaking down disciplinary boundaries to create an integrated process that addresses management goals in which community structure and other mechanistic factors could be examined as a whole. A system in this context is defined as a habitat, geographic area, human community or network of communities (Levins 1998). As complexity increases, the ability to gather quantitative information is complicated by the impracticality of the number of parameters to measure and the loss of realism (Levins 1966; Puccia and Levins 1991).

Qualitative models can simplify complex systems without sacrificing realism (MacArthur and Levins 1965; Levins 1966) and enable an integrated analysis of a system. Qualitative modeling in the form of signed digraphs, ‘loop analysis,’ and matrix analysis facilitates the understanding of a system where there is incomplete information. Because qualitative models involve only the signs of the interactions among variables (positive, negative, or no change), variables representing poorly quantified aspects of the system can be included in the analysis (Puccia and Levins 1991). Such variables represent not only different species, but also resources, climate, or socioeconomic variables that influence community structure and function. When constructing models, qualitative modeling methods can help determine which variables should be included, what should be measured, and how system dynamics might be affected under different perturbation (stresses that result in a permanent change in a growth parameter) scenarios (Levins 1998).

Loop analysis and the corresponding community matrix is a useful analytical tool for exploring and understanding the effects of natural and anthropogenic stress on a system. Dambacher et al. (Dambacher et al. 1999) used this modeling procedure to characterize a predator-prey system involving snowshoe hare and arctic fox. This technique also proved useful in predicting the impact of species introductions into a community (Li et al. 1999; Castillo et al. 2000) and explaining complex transitions in community composition over time (Bodini 1998; Ortiz and Wolff 2002). Loiselle et al. (2000; 2002)) used loop analysis to examine different economically-based management scenarios in a wetland ecosystem to identify management options and guide monitoring programs.

In the context of integrated risk, Levins (Levins 1998) extended qualitative modeling to the problem of vector-borne disease. In his system, he identified the invasiveness of vectors and disease reservoirs as core variables that would be important in an epidemic, adding vector habitat requirements, vector and host behaviour, host health status, and economic variables as other factors to be considered. With an increasing ‘web of causation,’ Levins (Levins 1998) argued that internal processes critical to community function could be examined. On further analysis of this problem, Orme Zavaleta and Rossignol (Zavaleta and Rossignol 2004) developed a procedure to predict disease risk that combines recent developments in qualitative community modeling with biomathematical theory of vector-borne disease transmission. This procedure predicts the change in risk of vector-borne disease following perturbations such as increases in vector abundance, animal control measures, habitat alteration, or global warming.

Like Levin's postulated epidemic-disease community, this procedure allows the consideration of a complex community structure linking ecological factors to human disease. This procedure results in a rigorous prediction of an ecological community response to a perturbation with minimal to no quantitative parameterization. It generates focused hypotheses to guide data collection and control management strategies as interventions.

Bayesian analyses in the form of Bayesian networks are another tool that can be useful in an integrated risk analysis. A Bayesian approach is based on probability theory and is a useful decision-making or inferential technique when there is incomplete information or it is not possible to gather enough information to reduce uncertainties (Reckhow 2003). A Bayesian network is used to model a system containing uncertainty. It offers both qualitative and quantitative information in the form of conditional probabilities and can be applied to multivariate problems involving complex relationships among variables (Reckhow 2003). A Bayesian network consists of a directed acyclic graph and a probability distribution. The network characterizes variable relationships through interrelated nodes and arcs. The nodes represent variables and the arcs represent conditional dependencies between the nodes. Bayesian networks are used to identify those key variables influencing relationships within a system, and thus are an integrative analytical tool.

The use of Bayesian networks is increasing in scientific analyses of complex problems. Crome et al. (Crome et al. 1996) applied a Bayesian approach to evaluate the impact of logging on bird and mammal species in rain forests. The investigators had too few data to detect potential impacts using traditional statistical analysis. However, results of a Bayesian analysis suggested a correlation between canopy cover and impacted bird species that was not previously apparent. Further, of the 76 species of birds in question, only four species were identified as having a high probability of being adversely impacted by logging.

Bayesian networks have also been used to guide such diverse analyses as land management decisions (Marcot et al. 2001), fish stock assessment (Varis et al. 1993; Hammond and Ellis 2002), and potential risk factors associated with heart disease (Buntine 1991). Each of these cases started with a hypothesized model that could be updated as additional information became available, and involved large uncertainties, the pooling of information from different datasets, and expert judgment in the analysis.

When a specific model is not known, a data discovery technique, Probablistic Relational Modeling (PRM), can conduct a heuristic search of independent data sets to generate data-derived models (Jorgensen 2003). This technique involves machine learning guided by expert judgment to develop a probabilistic model. The PRM extends Bayesian networks to the relational level, modeling uncertainty related to variables, their properties, and relationships among them (Getoor et al. 2001). The probabilistic relationship between variables is such that a change in any one variable affects all the others. Thus, PRMs are well suited for application to complex systems.

There are a few examples of where PRM has been used to evaluate complex problems. Getoor et al. (Getoor et al. 2001) described a PRM analysis to determine possible probabilistic relationships between patients from a tuberculosis clinic, certain risk factors, and specific strains of tuberculosis. In a second example, Jorgensen et al. (Jorgensen et al. 2003) used a PRM approach to explore the long-term changes in the clarity of Crater Lake using information summarized in multiple databases. The PRM analysis enabled the investigators to construct multiple, complex hypotheses concerning the entire lake ecosystem given data obtained from the long-term studies of the lake.

Probablistic Relational Modeling was also used by Orme Zavaleta et al. (Zavaleta in review) to identify probabilistic relationships associated with the transmission of West Nile virus in Maryland. Similar to the Crater Lake study (Jorgensen et al. 2003), the RBM approach was used to explore relationships among multiple, independent databases. Multiple hypotheses were generated suggesting spatial and temporal relationships between key vector, host and habitat variables related to disease transmission.

Thus, the PRM technique appears to be an effective means of conducting an integrated risk analysis through the qualitative and quantitative evaluation of complex community interactions. The hypotheses generated by the PRM analysis can be used to guide further quantitative testing of specific relationships between probabilistically linked variables.

Integrated Risk of CHABs

The concepts of integrated risk assessment can be applied to the problem of CHABs to help define the specific information, tools and research needed for effective decision-making and action. Although it would be presumptuous to attempt a fully developed assessment in this paper, communication of an initial conceptual model can facilitate the discussion and additional analyses required to advance such an assessment. The conceptual model in Figure 2 reflects existing knowledge about the factors contributing to blooms, the health, ecological and socioeconomic effects of blooms, and the linkages among important components of this multifaceted system. Different pathways of exposure and effect are shown for humans, wildlife, and aquatic plants and animals, as the processes influencing these groups of receptors vary. However, the pathways intersect to illustrate system linkages, or when biological processes are common to multiple receptor groups. Along the bottom row of the model are loose expressions of candidate assessment endpoints for an integrated risk assessment, reflecting some of the values whose protection may underlie the need for management action to control or mitigate CHABs.

Additional refinement of the conceptual model is required to advance an integrated assessment of the risks of cyanobacterial blooms. Are the important environmental processes and factors controlling blooms captured? Is the array of assessment endpoints important to the CHABs problem articulated fully? Are the key system components and their linkages described adequately? With agreement on the adequacy of the conceptual model, planning discussions can address the availability of tools and information required to evaluate critical risk hypotheses represented in the model, potentially leading to identification of additional data and research needed to complete the assessment. Though challenging, performance of a thoroughly-planned integrated risk assessment would support comprehensive decisions for managing the risks of CHABs.

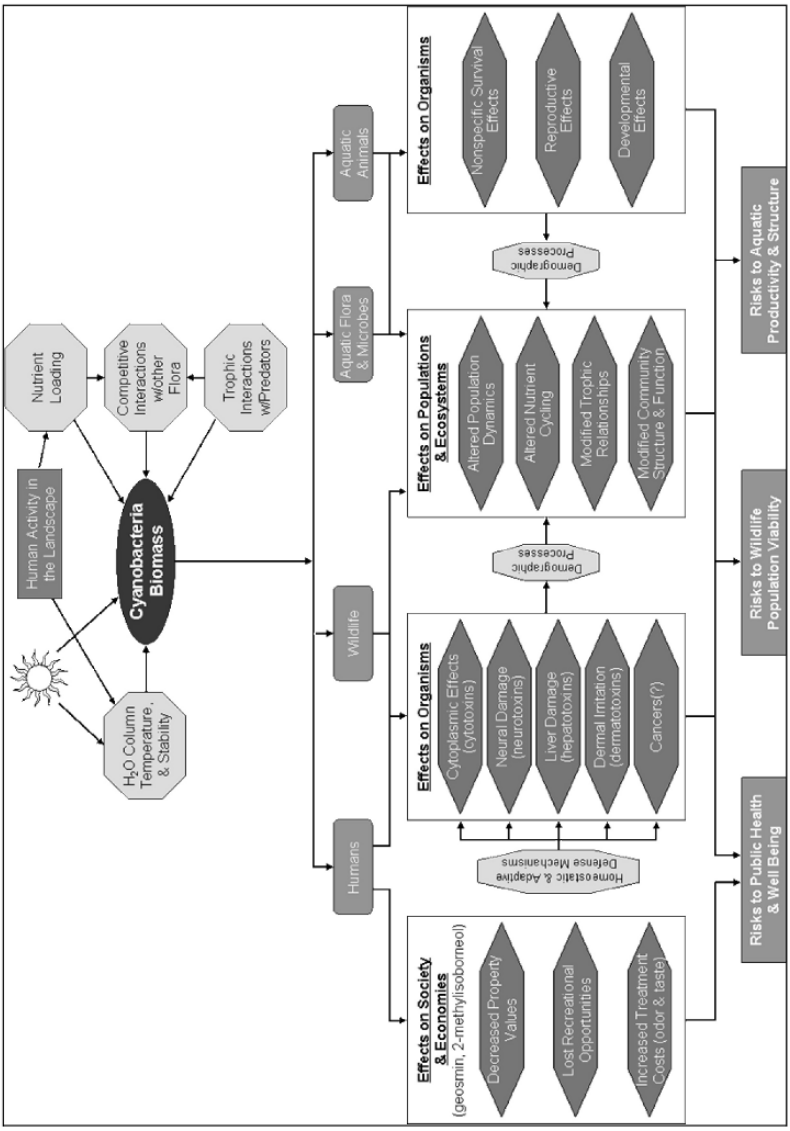

Fig. 2. Conceptual model for cyanobacterial harmful algal blooms.

Discussion

To conduct an integrated risk assessment of CHABs, a suite of tools is needed that integrates human and environmental health in the problem formulation (for hypothesis generation) and analysis phases of the assessment, not simply during the risk characterization phase. Such tools should consider the interacting system as a whole, from the environmental processes that influence CHAB formation to the changes caused by those blooms in the combined human and ecological system. Although this adds complexity in the analysis, models and other decision support methods are available that can simplify and reduce complexity.

The 'integrative' models reviewed in this paper may not be robust enough to integrate multiple stressors or multiple endpoints in their use of either parallel assessments or deductive reasoning to remove stressor interactions from consideration. The analytical techniques employed in these models to characterize risk are applied to either human health or ecological assessments. Qualitative modeling and Probablistic Relational Models provide an integrated risk analysis framework that identifies relationships important in the system and thus, guide the application of quantitative models or provide sufficient information for management decisions. Both techniques rely on community structure for generating hypotheses and testing predictions. Experimental comparison of various community theories suggests that loop analysis may be the theoretical approach best suited for predicting the behaviour of complex community structures following a perturbation (Hulot et al. 2000). Used in conjunction with mechanistic models, the integrated analytical techniques provide a balanced, iterative approach for not only assessing risk, but evaluating possible consequences of different CHABs management scenarios.

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