Human and Ecological Risk Assessment, 12: 66–73, 2006

ISSN: 1080-7039 print / 1549-7680 online
DOI: 10.1080/10807030500428595

Risk-Based Approaches to Managing Contaminants in Catchments

Barry T. Hart,[1] Mark Burgman,[2] Michael Grace,[1] Carmel Pollino,[1] Colette Thomas,[1] and J. Angus Webb[1]
[1]Water Studies Centre, Monash University, Australia; [2]Botany Department, University of Melbourne, Melbourne, Australia

ABSTRACT

Risk-based methods promise improved decision-making for managing of contaminants, such as salinity, sediments, nutrients, and toxicants, that can adversely affect the ecological condition of aquatic ecosystems. Two aspects of ecological risk assessment (ERA) and management—stakeholder involvement and more quantitative approaches to risk analysis—are particularly challenging. Stakeholder involvement is crucial both in the risk assessment process and the development, acceptance, and implementation of a risk management plan. Additionally, a number of quantitative approaches (particularly Bayesian approaches and multi-criteria decision-making) have been identified as having the potential to include expert-based inputs into risk-based decision-making. These offer promise for better inclusion of stakeholder knowledge and preferences into the decision-making process, and for improving the links between stakeholder inputs and potential risks to the ecological condition of the system. A major challenge for ecologists and natural resource managers is to make the ERA process more quantitative. Most ERAs conducted to date have been qualitative assessments that suffer from a number of deficiencies, the most serious being the lack of transparency and a reliance on subjective judgments. This article argues that the most productive way forward may be to use Bayesian methods to couple existing process-based models, empirical relationships based on good data, and expert opinion, to make the analysis of ecological risks more robust, consistent, and repeatable.

Key Words: ecological risk assessment, contaminants, cathment, stakeholders, Bayesian models.

INTRODUCTION

Effective management of waterways, wetlands, and estuaries is not possible without effective management of the catchment. It is now well accepted that many (but not all) of the factors (stressors, pressures) influencing the ecological condition of waterways come from the catchment.

Address correspondence to Barry T. Hart, Water Studies Centre, Monash University, Melbourne, Australia 3800. E-mail: barry.hart@sci.monash.edu.au

Management of contaminants within catchments is a difficult, multivariate problem involving multiple stressors, multiple ecological issues, and competing social priorities. There is considerable general knowledge regarding the cause-effect relationships between many of these stressors and the consequent ecological effects. For example, it is now well known that land clearing can resulting in rising water tables that in turn result in salinization of land and adverse impacts on downstream rivers and wetlands (Cramer and Hobbs 2002). Additionally, there is a considerable amount known about the environmental effects when such cleared land is used for agriculture. This invariably leads to increased loads of suspended sediment and nutrients being transported from the catchment into downstream rivers, wetlands, and estuaries, often causing unwanted algal blooms. Also, much is known about the potential adverse environmental effects of irrigation schemes, effects such as adverse changes to river flow regimes and the release of contaminants such as salinity, nutrients, sediment, and pesticides (Hart 2004).

However, despite this quite considerable general knowledge about the ecological effects of contaminants or stressors generated in catchments, we still lack well accepted, quantitative and predictive cause–effect models that can assist natural resource managers to better manage catchments. Such models will become increasingly important in resolving differences between stakeholders with competing interests.

Risk-based approaches are increasingly being used by catchment managers to improve the decision-making in these multi-issue situations (Hart *et al.* 2001; Burgman 2004). For example, the new ANZECC water quality guidelines have adopted a risk-based approach (ANZECC 2000), as has the Victorian Environmental Protection Agency in the development of the new *State Environmental Protection Policy* (Waters of Victoria) (Vic EPA 2003). Also the irrigation industry, through the National Program for Sustainable Irrigation, has developed ecological risk assessment guidelines to assist their industry work toward more environmentally sustainable practices (www.lwa.gov.au/irrigation/research; Hart 2004; Hart *et al.* 2005).

In this article, we first outline the basic principles underpinning ecological risk assessment (ERA) and management, and then discuss the challenges facing two key aspects of this process, namely the involvement of key stakeholders in the process, and particularly in problem identification, and the drive to make the risk analysis part of the ERA process more quantitative and to identify (and quantify) the uncertainties. We suggest a system for risk analysis in which stakeholders are not alienated by technical details, and in which the final result is vetted by mathematical reasoning and is consistent with the available data and scientific understanding.

ECOLOGICAL RISK ASSESSMENT

Ecological risk is defined as the product of the likelihood (or probability) of some adverse event (hazard) occurring and the ecological consequences that result if the event does occur (*i.e.*, ecological risk = likelihood × consequence).

Generally, there are three stages in undertaking an ecological risk assessment (USEPA 1998; Hart *et al.* 2003, 2005): (a) problem formulation, (b) risk analysis, and (c) risk characterisation. These are shown in Figure 1.

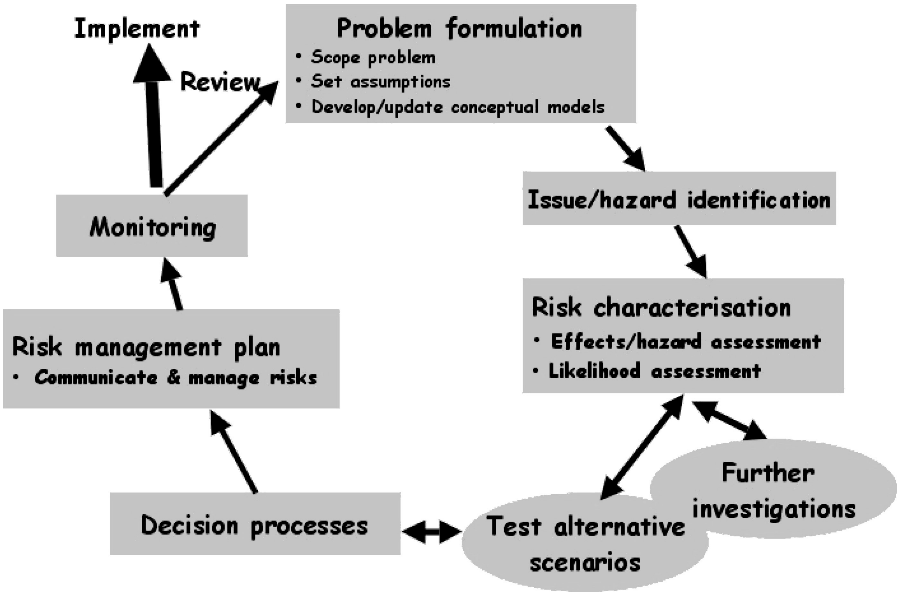

Figure 1. Stages in undertaking an ecological risk assessment.

In brief, the ERA process seeks to:

- Set the context, formulate the problem, and identify what is at issue and who is affected by decisions;
- Identify the key ecological issues and key stressors
- Identify the linkages between the key stressors (drivers) and each ecological consequence (using first a conceptual model and then preferably a quantitative ecological model). The model will provide information on how these drivers will respond to management and other changes in the environment, what important knowledge gaps exist, and what are the best assessment “endpoints” to use in the risk assessment.
- Assess the risks associated with each issue (*i.e.*, the likelihood that the issue will occur and the consequences if it does occur) as quantitatively as possible,
- Identify (and where possible quantify) all major uncertainties so the decision-maker can decide on the confidence that should be placed on the information.

As shown in Figure 1, the information from the risk assessment feeds into the decision-making process where this information is coupled with other relevant economic and social information to develop a risk management plan. This adaptive management plan includes a robust monitoring program and review process to assist the manager and the stakeholders to assess the effectiveness of the plan and to update and improve management as information becomes available on the effectiveness of the actions implemented.

Two of the most challenging aspects of this ecological risk assessment and management process, discussed in this article, are:

1. The *problem formulation step,* particularly in those situations where there are multiple stressor and multiple ecological effects, which needs improved methods for involvement of stakeholders; and
2. The *risk analysis step,* which needs to have continuing involvement of the stakeholders and be more quantitative.

STAKEHOLDER INVOLVEMENT

Management of natural resources should aim to benefit all resource users as equitably as possible, within the constraint that the use is sustainable and does not lead to unwanted degradation of the resource (*e.g.*, land) or the external environment (*e.g.*, downstream wetlands).

As noted earlier, this is a difficult task within catchments as there are often many different activities (*e.g.*, forestry, irrigation, dryland agriculture, tourism, urban) each contributing different stresses on the environment. These stresses need to be integrated to assess how each influences the ecological condition of the surface and groundwater resources (and wetlands and estuaries) in the catchment.

A common failing with many catchment management strategies is that they are developed without the participation of local individuals and institutions, and so do not take into account the motivations of these important groups. The resulting lack of stakeholder cooperation undermines any delivery mechanisms designed to implement the management plan and the potential benefits fail to be realized (Cain *et al.* 1999).

While key stakeholders should be kept involved throughout the entire risk assessment process, it is particularly important that they are actively involved in the problem formulation step. The problem formulation step is particularly difficult in those situations where there are multiple stressor and multiple ecological effects. Part of the difficulty arises because people bring different values and different conceptual models to the discussion. Usually, data and understanding are not available to discriminate between them or to resolve differences. Even if they were, different values would preclude consensus. Such issues cloud the ability of individuals or groups to develop satisfactory priorities in ranking and dealing with potential hazards. We suggest that stakeholders be encouraged to state their beliefs verbally and that these be captured in alternative conceptual models. These models can be cross-examined by other stakeholders and if they survive scrutiny, they should be retained until such time as there is substantial contrary evidence.

Although most ecological risk assessments now involve key stakeholders, we believe this is often poorly done. Some of the problems we have observed include:

- Failure to involve important, but often “difficult,” individuals or groups of stakeholders. This leads to these groups questioning the credibility of the process (often through the press);
- Failure to take notice of legitimate issues brought forward by stakeholders;
- Failure to account for long-standing disagreements between “competing” stakeholder groups;

- Failure to put the necessary effort into informing and running the stakeholder workshops, resulting in key groups being disillusioned with the process and feeling alienated; and
- Failure to allow the stakeholders to drive the identification of the issues or hazards that need to be considered (*e.g.*, where the issues have been largely decided prior to the involvement of stakeholders, leading to a "lip service"-type stakeholder involvement).

Almost all ecological risk assessments are run by technical teams dominated by biophysical scientists (*e.g.*, ecologists, hydrologists, chemists, engineers). Rarely are *social scientists* involved in these teams, despite the fact that elicitation of information from stakeholders is largely a social science activity.

We believe strongly that most ERAs would be improved by the involvement of a social scientist. Stakeholder elicitation is their area of expertise and is not an area of expertise of most biophysical scientists.

It is essential that adequate thought, effort, and expertise is put into stakeholder involvement in the ERA process, and particularly how stakeholders will be involved in the important first step of problem formulation. There are many well-tried and tested methods available for eliciting information from stakeholder and community groups, including stakeholder analysis (Grimble and Wellard 1997; Glicken 2000), adaptive management (Maguire 2003), multicriteria decision making (Fernandes *et al.* 1999; Roy 1999), and Bayesian approaches (Borsuk *et al.* 2001; Bacon *et al.* 2002).

We believe that methods that explicitly include stakeholder inputs into risk-based decision-making, such as those based on Bayesian and multicriteria decision-making approaches, would significantly strengthen the process.

TOWARD MORE QUANTIFICATION OF ECOLOGICAL RISKS

The risk analysis step involves bringing together the consequences and likelihood of each adverse effect occurring. The inherent frailties in subjective estimation of probabilities and consequences are now well established (Burgman 2001, 2005; Suter 1993). Rationalization of ideas depends on ensuring arguments and conceptual models are internally consistent and consistent with whatever data and ecological principles are available. The only realistic way to achieve this in most settings is to develop explicit quantitative models.

The cost is that these models typically alienate stakeholders, critical in problem formulation and adoption. We suggest that stakeholders should create the (conceptual) models and that technical experts should subordinate their role to the needs and views of those affected by decisions. Experts should evaluate the internal consistency of these models and project their outputs, so that stakeholders can see the consequences of what they believe to be true.

Although the deficiencies of qualitative risk analysis have been well documented, many of the tools to make this process more quantitative are poorly developed, inappropriate or full of hidden assumptions (Burgman 2001, 2005). This is particularly so when attempting to assess the ecological risks associated with contaminants generated from multiple sources within a catchment. The processes we wish to better understand in catchments are both complex and inherently variable (most are driven by climate).

An increasing number of process-based (bio)physical models are now available that do a reasonable job in predicting the generation and transport of contaminants such as salt, sediment, and nutrients. Examples include the CRC for Catchment Hydrology models EMSS and SEDNet (www.catchment.crc.org.au), salt transport models, and eutrophication models (Walter *et al.* 2001).

These models still have three major deficiencies:

1. They are still not able to address multiple stressors in any systematic way,
2. They rarely treat uncertainty explicitly, and
3. They rarely couple the contaminant with its ecological effect, particularly in downstream waterways, wetlands, and estuaries (*e.g.*, poor quantitative cause-effect models).

We are confident that those researchers committed to these process-based models will address deficiencies associated with multiple stressors and uncertainty over the next few years.

However, given the inherent complexity and lack of knowledge about many of the basic processes and relationships between contaminants and biota, we believe that other types of models may offer more promise for progress. Perhaps the most promising of the alternative modeling approaches are those using Bayesian techniques (Reckhow 2003).

Bayesian models can assist with multiple stressor problems, in that they are able to incorporate information with high uncertainty, including poor or incomplete understanding of the system, and can include both empirical data and expert opinion. And most importantly, prior probabilities can be updated as more information becomes available.

Bayesian models have been successfully used for a wide range of risk predictions, including relating catchment nutrient management actions to algal bloom formation in the Neuse River estuary, North Carolina (Borsuk *et al.* 2004), assessing native fish abundance in the Goulburn River (Pollino *et al.* 2006), survival of an estuarine clam in anoxic bottom waters (Borsuk *et al.* 2002), assessing New Zealand abalone stocks (Breen *et al.* 2003), and assessing fish and wildlife viability under land management alternatives (Marcot *et al.* 2001).

Interestingly, the work by Borsuk *et al.* (2004) illustrated well the need to consider models at a range of scales in order to account for the predictable patterns that can emerge at a variety of scales. Thus, they used a Bayesian network to integrate a number of models of the various processes involved in eutrophication of an estuary. They integrated process-based models statistically fitted to long-term monitoring data, Bayesian hierarchical modeling of cross-system data gathered from the literature, multivariate regression modeling of mesocosm experiments and judgments elicited from scientific experts.

The Bayesian network approach allowed the outputs from these disparate models to be integrated into a cohesive overall model that related nitrogen inputs to the river to endpoints that were identified as important by stakeholders.

REFERENCES

ANZECC. 2000. Australian and New Zealand Water Quality Guidelines. Canberra, Australia, and New Zealand Environment and Conservation Council & Agriculture and Resource Management Council of Australia and New Zealand, Canberra, Australia.

Bacon PJ, Cain JD, and Howard DC. 2002. Belief network models of land manager decisions and land use change. J Environ Manage 65(1):1–23

Borsuk M, Clemen R, Maguire L, *et al.* 2001. Stakeholder values and scientific modeling in the Neuse River watershed. Group Decision & Negotiation 10:355–73

Borsuk ME, Powers SP, and Peterson CH. 2002. A survival model of the effects of bottom-water hypoxia on the population density of an estuarine clam (Macoma balthica). Canadian J Fisheries and Aquatic Sciences 59(8):1266–74

Borsuk ME, Stow CA, and Reckhow KH. 2004. A Bayesian network of eutrophication models for synthesis, prediction, and uncertainty analysis. Ecol Modelling 173:219–39.

Breen PA, Kim SW, and Andrew NL. 2003. A length-based Bayesian stock assessment model for the New Zealand abalone Haliotis iris. Marine Freshwater Res 54(5):619–34

Burgman MA. 2001. Flaws in subjective assessments of ecological risks and means for correcting them. Aust J Environ Manage 8:219–26

Burgman MA. 2005. Risks and Decisions: For Conservation and Environmental Management. Cambridge University Press, Cambridge, UK

Cain J, Batchelor C, and Waughra, D. 1999. Belief networks: a framework for the participatory development of natural resource management strategies. Environ Development & Sustainability 1(2):123–33

Cramer VA and Hobbs RJ. 2002. Ecological consequences of altered hydrological regimes in fragmented ecosystems in southern Australia: Impacts and possible management responses. Austral Ecol 27:546–64

Fernandes L, Ridgley MA, and van'tHoff T. 1999. Multiple criteria analysis integrates economic, ecological and social objectives for coral reef managers. Coral Reefs 18:393–402

Glicken J. 2000. Getting stakeholder participation 'right': a discussion of participatory processes and pitfalls. Environ Sci Policy 3:395–410

Grimble R and Wellard K. 1997. Stakeholder methodologies in natural resource management: a review of principles, contexts, experiences and opportunities. Agricultural Systems 55:173–93

Hart BT. 2004. Environmental risks associated with new irrigation schemes in Northern Australia. Ecological Management & Restoration 5:107–11.

Hart BT, Grace MR, Breen P, *et al.* 2001. Application of ecological risk assessment in river management. In: Rutherfurd I, Sheldon F, Brierley G, *et al.* (eds), Proc Third Australian Stream Management Conference—Value of Healthy Streams, pp 289–95. CRC for Catchment Hydrology, Melbourne, Australia

Hart BT, Lake P S, Webb A, *et al.* 2003. Use of risk assessment to assess the ecological impacts of salinity on aquatic systems. Aust J Botany 51:689–702

Hart BT, Burgman M, Grace M, *et al.* 2005. Ecological Risk Management Framework for the Irrigation Industry, Technical Report, Land & Water Australia, Canberra, Australia (available www.sci.monash.edu.au/wsc)

Maguire L. 2003. Interplay of science and stakeholder values in the Neuse River total maximum daily load process. J Water Resources Planning Manage 129:261–70

Marcot BG, Holthause, RS, Raphael MG, *et al.* 2001. Using Bayesian belief networks to evaluate fish and wildlife population viability under land management alternatives from an environmental impact statement. Forest Ecol Manage 153:29–42

Pollino CA, Woodberry O, Nicholson AE, Korb KB, Hart BT. 2006. Parameterisation and evaluation of a Bayesian network for use in an ecological risk assessment. Environmental Modelling & Software (*in press*)

Reckhow KH. 2003. Bayesian approaches to ecological analysis and modelling. In: Canham CD, Cole JJ, and Lauenroth WK (eds), Models in Ecosystem Science, pp 168–83.. Princeton University Press, Princeton, NJ, USA

Roy B. 1999. Decision-aiding today: what should we expect? In: Gal T, Stewart TJ, and Hanne T (eds), Multicriteria Decision-Making: Advances in MCDM Models, Algorithms, Theory and Applications, pp 1–35. Kluwer, Boston, MA, USA

Suter GW. 1993. Ecological Risk Assessment. Lewis Publishers, Chelsea, MI, USA

USEPA (US Environmental Protection Agency). 1998. Guidelines for Ecological Risk Assessment. EPA/630/R-95/002F. Washington, DC, USA

Vic EPA. 2003. State Environmental Protection Policy (Waters of Victoria). No. S107-WoV. Environment Protection Authority, Melbourne, Australia

Walter M, Recknagel F, Carpenter C, *et al.* 2001. Predicting eutrophication effects in the Burrinjuck Reservoir (Australia) by means of the deterministic model SALMO and the recurrent neural network model ANNA. Ecol Modelling 146:97–113