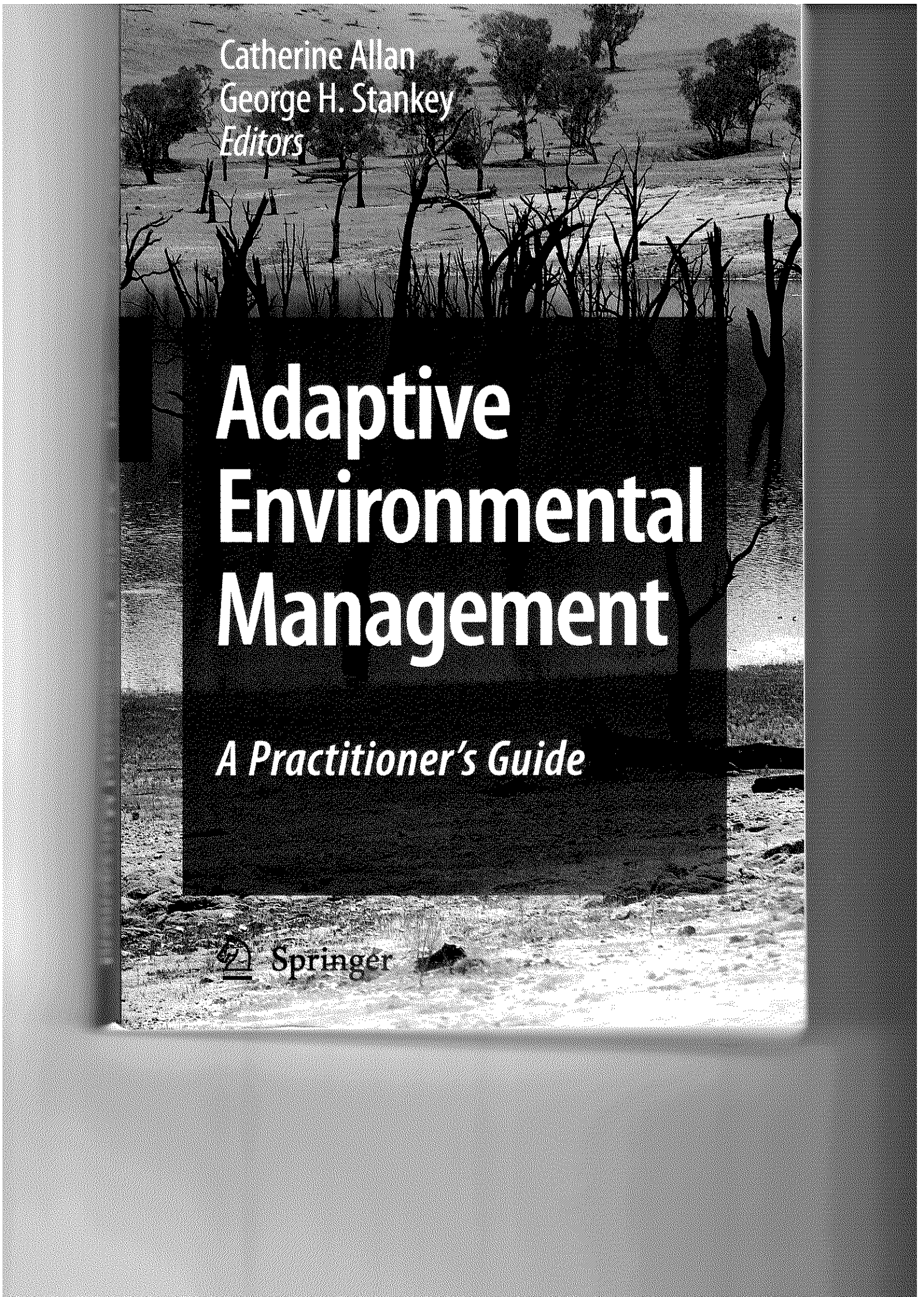
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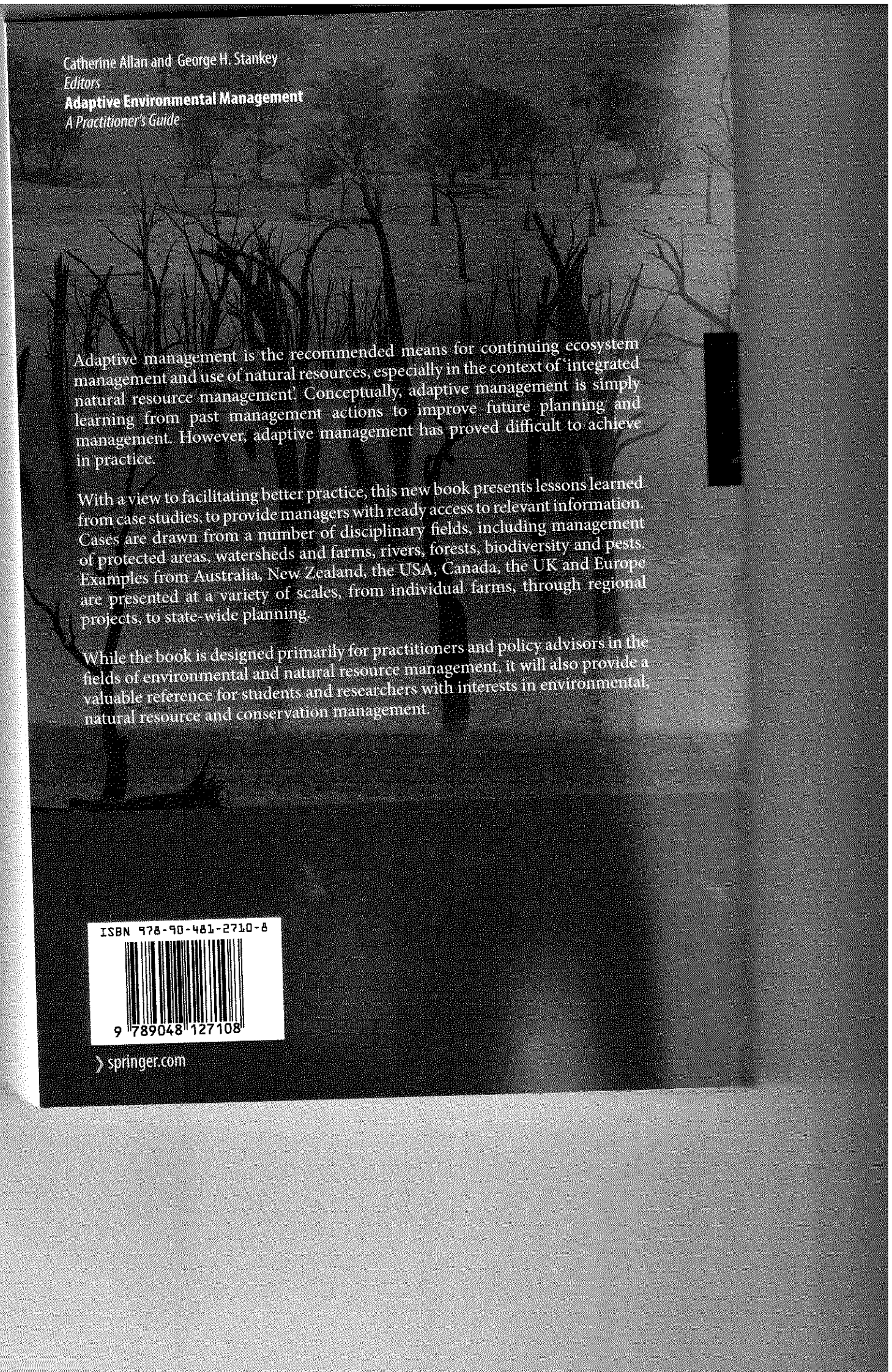

Catherine Allan and George H. Stankey
Editors

Adaptive Environmental Management
A Practitioner's Guide

Adaptive management is the recommended means for continuing ecosystem management and use of natural resources, especially in the context of 'integrated natural resource management'. Conceptually, adaptive management is simply learning from past management actions to improve future planning and management. However, adaptive management has proved difficult to achieve in practice.

With a view to facilitating better practice, this new book presents lessons learned from case studies, to provide managers with ready access to relevant information. Cases are drawn from a number of disciplinary fields, including management of protected areas, watersheds and farms, rivers, forests, biodiversity and pests. Examples from Australia, New Zealand, the USA, Canada, the UK and Europe are presented at a variety of scales, from individual farms, through regional projects, to state-wide planning.

While the book is designed primarily for practitioners and policy advisors in the fields of environmental and natural resource management, it will also provide a valuable reference for students and researchers with interests in environmental, natural resource and conservation management.

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Adaptive Environmental Management

A Practitioner's Guide

Springer

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Part I
Understanding Adaptive Management

Chapter 9
Modelling and Adaptive Environmental Management

Tony Jakeman, Serena Chen, Lachlan Newham, and Carmel A. Pollino

Abstract Models can be used to synthesise our understanding of a system and facilitate the exploration of possible impacts of changes in management, climate and other factors. Modelling can also be an effective process in helping to identify knowledge gaps and prioritising monitoring requirements and management options. Accordingly modelling can be a valuable tool in assisting adaptive management. Model development should follow a rigorous approach to enhance relevance and credibility, particularly when models are used to guide management decisions which require defensibility. Appropriate stakeholder involvement throughout the model development process can be an effective means of social learning and consensus building. Working in collaboration with all stakeholders helps to ensure the model is appropriately focussed, and is more likely to produce recommendations acceptable to the decision makers and community.

Integrated modelling is useful in informing decision making for systems involving complex, multi-sectoral issues. These models can also be applied for purposes such as prediction, forecasting, system understanding and social learning. The main integrated modelling approaches include Bayesian networks, coupled components models, expert systems, agent-based models and system dynamics. The selection of approach must depend on the purpose of the modelling exercise, the available knowledge and data on the system, the timeframe and the technical resources available. Integrated approaches promote stakeholder engagement, systems thinking and transparency, and can therefore be an effective tool in adaptive management.

Introduction

Observational data and existing knowledge are rarely sufficient in fully assessing the health of a complex natural system and its causal relationships. At best, data tend to be too limited in scope and knowledge too compartmentalized for this purpose.

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Modelling is a scientific process of simplifying reality to enhance understanding through the structuring of data, knowledge and assumptions in a creative and disciplined way for a specific purpose. Models can systematically integrate and capture our understanding of how changes in management, climate, demographics and other factors affect selected indicators of system health so that the consequences of management options can be clarified. Models can be qualitative, quantitative, or a combination of the two. The more complex the system being considered, the greater the role for models to account for the interactions among drivers, processes and associated outcomes. On the other hand, models are imperfect representations and the nature of the systems they attempt to describe may change over time. But new knowledge and data, appropriately targeted, almost always benefits model usefulness, as does a rigorous approach to the model selection and development procedure.

The challenge is to view and implement modelling as an ongoing scientific and participatory process that serves adaptive management. In this connection the first aim of modelling should be to identify new knowledge and data needs that will lead to further understanding, if not direct clarification, of the impacts of various courses of action on system health. As far as possible another aim should be to assist obtaining consensus on, or defensibility of, the management decisions to be taken. As argued in section "A Rigorous Approach to Modelling Practice" of this chapter, such aims demand good modelling practice, especially in the selection of a model type and approach that recognizes context, a topic covered in section "Participatory Processes and Adaptive Management". It also calls for the use of participatory processes (section "Selecting the Appropriate Modelling Approach") and analytic tools (section "Sensitivity Assessment") that help identify the type of data, knowledge and associated experiments that gives leverage to achieving the first aim. For practical reasons, it also should take into account the cost-effectiveness of acquiring this new knowledge.

Few would disagree that adaptive management needs more emphasis and strategic research. To this end, modelling and its incorporation in information or decision support systems (section "Information and Decision Support Systems"), can aid the development of: (i) ways to gather, record and share conventional and unconventional environmental system information; (ii) improved tools to capture and express qualitative as well as quantitative knowledge; (iii) methods for testing knowledge, identifying gaps and designing experiments; (iv) monitoring techniques able to distinguish the effects of changed management practices from the large natural variations associated with most systems; and (v) approaches to screening and testing a broad range of alternative policies.

Two examples are given in this chapter of the value of integrated modelling for adaptive management. In section "An Illustrative Problem in Catchment Management" we report on the management of sediments and nutrients to protect catchment and estuarine water quality, and in section "Vegetation Management in a Conservation Reserve" we examine a study of vegetation management in a conservation reserve. Some of the barriers to enhancing the use of modelling for adaptive management are discussed in section "Barriers to Modelling for Adaptive Management". Section "Conclusions" constitutes the conclusions.

Modelling in the Adaptive Management Process

Modelling can be a useful tool at various stages of the adaptive management process outlined in Chapter 2 of this volume (Fig. 9.1). During the planning stage, models can be used to scope the problem and synthesize available knowledge and data on the system. Models are inherently subjective, and should incorporate uncertainties in the understanding of system processes and in the parameter estimates (Sutherland, 2006). Walters et al. (2000) suggested that the two key roles of modelling in adaptive management were: (1) to reveal gaps in understanding and data, and (2) to guide prioritization of experimental management options and monitoring. Identifying the knowledge gaps may subsequently help direct the experimental design to further system understanding.

Simulation models can be valuable tools in linking science and management (Rivers-Moore & Jewitt, 2007). McLain and Lee (1996) examined three case studies of adaptive management: (1) spruce budworm management in New Brunswick, Canada, (2) fisheries management in British Columbia, Canada and (3) fisheries management in Columbia River Basin, US. In each of the three cases, the most useful role of modelling was found to be in facilitating the exploration of possible impacts of different management scenarios. Although model predictions are never completely reliable, they can help to stimulate thought and further research. For example, if a model failed to predict an extreme event, understanding the reasons why can help in improving subsequent predictions and thus system understanding (Sutherland, 2006). Given that the outcomes are limited by model assumptions, McLain and Lee (1996)

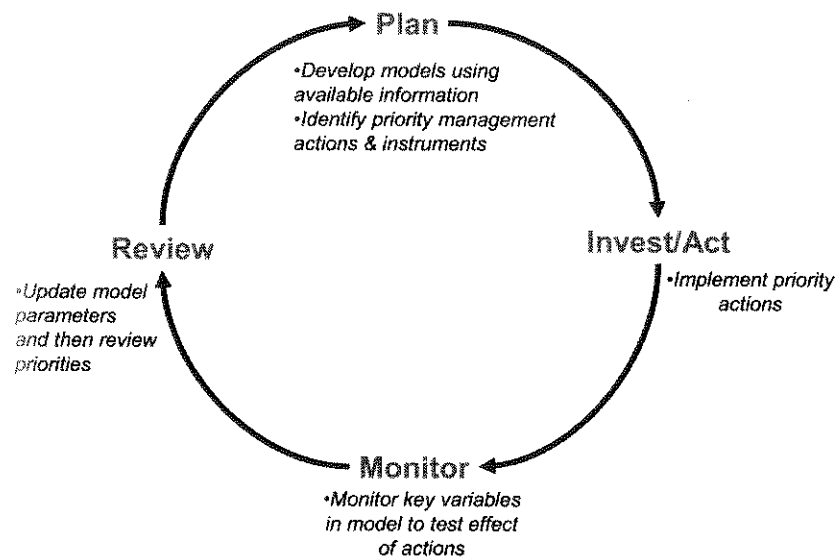

Fig. 9.1 Models as tools in the adaptive management process

also suggested that comparing multiple competing models may be useful in understanding how these underlying assumptions affect model results.

The Coastal Lake Assessment and Management (CLAM) tool is an integrative decision support tool for exploring tradeoffs associated with the management of coastal lakes in New South Wales, Australia (Ticehurst, 2008; Ticehurst et al., 2007). Using a Bayesian network framework (see sections "Selecting the Appropriate Modelling Approach" and "Vegetation Management in a Conservation Reserve"), the model can be used to determine which management actions are likely to produce the most desirable outcomes, and should thus be implemented. The CLAM tool can also help identify which system components are likely to be affected by these actions (given current knowledge), and thus identifies which key variables should be monitored. The resulting monitoring data can then be used to update the model parameters, to improve reliability of the tool for future runs. Models can also facilitate social learning and consensus building, as discussed further in section "Participatory Processes and Adaptive Management".

A Rigorous Approach to Modelling Practice

Good modelling practice can only increase the relevance, credibility and impact of the information and insight that modelling aims to generate. It is a necessity for long-term, systematic accrual of a good knowledge base for both scientific understanding and decision making. Jakeman et al. (2006) recommend a minimum set of standards for good modelling practice that includes:

- Clear statement of the objectives and clients and interest groups of the modelling exercise
- Documentation of the nature (identity, provenance, quantity and quality) of the data used to drive, identify and test the model
- A strong rationale for the choice of model families and features (encompassing alternatives)
- Justification of the methods and criteria employed in model calibration
- As thorough analysis and testing of model performance as resources allow and the application demands
- A resultant statement of model utility, assumptions, accuracy, limitations, and the need and potential for improvement and
- Fully adequate reporting of all of the above, sufficient to allow informed criticism

Adoption of these standards by modellers would benefit not only the model-building community but also those relying on model-based insight and model recommendations to make decisions. Models must also be applied according to their purpose and capabilities. Their misuse can lead to results of low confidence and invalid conclusions.

Participatory Processes and Adaptive Management

Managers and interest groups can also potentially benefit from use of a model to define the scope of a problem, to make assumptions explicit, to examine what is known and what is not, and to explore possible outcomes beyond the obvious ones. If models are accessible enough, they can act as a medium for wider participation in environmental management. Accessibility might be enhanced in different ways, such as through a reliable technical platform for the scientific users or in user friendly software such as decision support systems for stakeholders (see section "Sensitivity Assessment").

Aside from equity and justice principles, there are two main reasons for increased stakeholder participation in model development. The first is to improve the modellers' understanding, allowing a broader and more balanced view of the management issue to be incorporated in the model. The second is to improve adoption of results from the assessment, increasing the likelihood of better outcomes, as model development becomes an opportunity for stakeholders to learn about interactions in their system and the likely consequences of their decisions.

Stakeholder participation in the past has often been limited to researchers wishing to exploit the results of the modelling exercise. A better approach, increasingly employed, is to involve all stakeholders throughout model development in a partnership, actively seeking their feedback on assumptions and issues and exploiting the model results through feedback and agreed adoption. This approach is expensive in effort, time and resources, but the aim of modelling is often to achieve management change, and the learning process for modellers, managers and other stakeholders inherent in this approach is essential to achieving change. Examples of such participation in model development can be found in, Hare et al. (2003), Letcher and Jakeman (2003) and Newham et al. (2006).

Selecting the Appropriate Modelling Approach

Selecting a modelling approach depends firstly on our objectives for the problem of interest. Let us assume that broadly the purpose is prediction and/or decision making that involves complex, multi-sectoral issues and tradeoffs where impacts are a function of potential management interventions and uncontrollable drivers such as climate. In such a case we would also be interested in social learning of interest groups (see section "Participatory Processes and Adaptive Management") to be a necessary component to achieve our objectives. In this way the accrual and sharing of knowledge and the potential for adoption of the management are enhanced. Along with purpose, the choice of a modelling approach also depends on the type of knowledge and data at our disposal, the resources for the modelling exercise and timeframe for an outcome or decision to be achieved. Generally we are not talking about hard science or disciplinary models here.

Nor are we talking about the significance or power of a hypothesis test as to whether an intervention will have an individual effect of some sort or not (e.g., Field et al., 2007). We are using integrated models of systems to guide our understanding.

Several approaches suggest themselves for such objectives and five major types are discussed by Jakeman et al. (2007). Table 9.1 indicates their suitability in different contexts. Two very different approaches are the Bayesian Networks (BNs) and the Coupled Component models (CC) approaches.

BNs are well-suited to integrating multiple issues, interactions and outcomes. A network connects system variables (inputs, internal states and outputs), portraying the cascading influences and interactions, starting with key drivers affecting internal system states and their influence on outcomes that are the object of our management. They allow the variables in models to be characterised according to the level of knowledge we have, so they can be expressed either quantitatively, qualitatively (e.g. categorically such as high-medium-low) or both. Relationships between variables are represented probabilistically. The latter allows uncertainty to be characterised and propagated through the network. BNs are well-suited to static representations of systems that are lumped in space but some detail in time and space can also be accommodated. A real strength is their utility to map the system representation with stakeholders and 'parameterise' them iteratively. Because interactions between adjacent variables are related by probabilities, one can populate them with whatever information is at hand, and as it accrues. One can utilize outputs from component models to assign the probabilities, or indeed use best qualitative knowledge as might be elicited from experts. Sensitivity and other analyses (see section "Sensitivity Assessment") can be used to infer where the weak points in the network model of the system are and subsequently design the 'experiments' to improve this information. The example in section "Vegetation Management in a Conservation Reserve" illustrates some of the valuable utility of BNs for adaptive management.

CCs on the other hand are most suited to handle problems where a small number of issues are being investigated at a high level of spatial and/or temporal detail (see the example in section "An Illustrative Problem in Catchment Management"). This approach combines detailed component models from different disciplines, which are linked through the sharing of outputs and/or inputs. Uncertainties typically are handled by brute force such as undertaking multiple runs through sampling from the distribution of their parameters. Because of their complexity, they are less suited to social learning and knowledge sharing, but careful handling such as through meta-modelling can overcome the difficulties. A simple but powerful approach could be using information from CCs to populate a Bayesian network that captured the key interactions, and using this version of the system with interest groups.

Both approaches are very well-suited to adaptive management, as illustrated in the following case studies. Agent-based models are an approach somewhere between BNs and CCs. They are essentially a form of CC that is concerned with the interactions between 'agents' (individuals) in a system. The agents are software components containing code and data, and adapt to changes to their environment. Multi-agent systems comprise a network of interacting agents, where individual

Table 9.1 Appropriate use of integrated modelling approaches

Approach	Data types	Resources required (technical and data)	Suitability to handle uncertainty	Space treatment	Time treatment	Breadth versus depth of interactions	Application
Coupled components	Quantitative	Medium to high	Computationally demanding	High	High	Depth of processes	Prediction
							Forecasting
							Decision making
							System understanding
							Social learning
Expert systems	Qualitative and quantitative	Low to high depending on the state of the knowledge base	Explicit	Medium	Variable	Compromise	Prediction
							Forecasting
							Decision making
							System understanding
							Social learning
Agent-based	Quantitative	Medium to high	Implicit	Medium	High	Both	System understanding
							Social learning
Bayesian networks	Qualitative and quantitative	Low to high	Explicit	Medium	Low	Both	Prediction
							Decision making
							System understanding
							Social learning
System dynamics	Qualitative	Low to high	Implicit	Medium	High	Both	Decision making
							System understanding
							Social learning

agents share information, request services and negotiate with each other. Agent-based models are capable of modelling complex systems containing multiple interactions among dynamic and autonomous entities. They are useful for social learning, particularly at revealing large-scale outcomes resulting from local interactions between individuals. Uncertainty is handled by brute force. The models are generally hypothetical and tend not to be as suitable as BNs or CCs for prediction. Rather they are useful for representing complex systems involving several stakeholders and allow exploration of the possible effects of alternative management options.

System dynamics are a popular modelling approach used by applied scientists because they allow investigation of complex feedback systems, such as food webs. System dynamic models can represent complex links within the human-biophysical environment, including nonlinearities, feedback loops, and spatial and temporal lags (Costanza & Ruth, 1998). Such phenomena can be difficult to represent with most other modelling approaches. They can also include poorly understood processes, represented as 'plausible' connections. System dynamic models are most commonly applied to improve system understanding, to compare alternative system assumptions, or for social learning. Theoretically, system dynamics approaches can also be used for decision-making and policy development.

Another type of qualitative model is expert systems, which simulates the problem-solving behaviour of domain-specific experts. Prior knowledge is encoded into a knowledge base and the expert system then uses logic to infer conclusions to the given problem. The success of the expert system is thus determined by the knowledge base (Forsyth, 1984). This approach is therefore unsuitable for modelling systems containing complex interactions and poorly understood processes. Expert systems can be applied to problems where there is little interaction between variables and where experts can articulate decisions with confidence. Uncertainty can be incorporated into expert systems by assigning uncertainty values (e.g. probabilities, belief functions, membership values) to the facts and rules. A powerful attribute of expert systems is their ability to explain, by retracing the steps of reasoning used to arrive at the conclusion.

A range of model integration frameworks and analysis tools already exist as a basis to help address the needs of adaptive management and in particular the iterative and integrated assessment of the environmental, social and economic impacts of management decisions. Their potential to clarify options and generate partnerships has already been demonstrated in various case studies (e.g., Jakeman & Letcher, 2003) but there is still a need to develop them further by adapting them to new case studies tuned to the needs of adaptive environmental management.

Sensitivity Assessment

In classical experiment design, the approach to gain knowledge is to choose some forcing to optimise a measure of accuracy of estimated parameters (usually based on an estimated covariance matrix). For natural resource management this

approach is problematic as it assumes some freedom in choice of the forcing (size, timing, location, form), and requires explicit modelling of error sources, structure and probabilistic properties. NRM modelling tends to involve heterogeneous errors and at best offers very limited control over the forcing that can be exercised. So we need an iterative experiment design procedure, focused largely on designing and/or revising the measurement regimes. In the example in section "An Illustrative Problem in Catchment Management" this involves integrating into the modelling the results of geochemical tracing and the collection and analysis of event-based water quality data in the waterways.

Sensitivity assessment (SA) of models is a key tool to inform modelling for adaptive management. It provides an objective means of assessing and improving modelling and is particularly useful in identifying high leverage data collection activities i.e. what new knowledge is most needed. Equipped with such information the necessary measurement and/or monitoring program can be designed within resource constraints. There is a wide body of techniques (see Saltelli et al., 2000) now available for SA but essentially they are all aimed at identifying the relations between changes in "factors" (values of forcing, parameters and/or boundary conditions) and resulting changes in model outputs, conclusions or internal variables. It is worth emphasizing that SA is a first step in formal uncertainty analysis which additionally requires the prescription of uncertainties in causes, usually as probability distributions, so that output distributions can be calculated.

So why perform SA?

- To see which factors are critical, which are uninfluential or redundant in determining modelled outcomes; check against prior knowledge
- To examine interactions, see what parts of the model are more or less independent
- To see how model structure could be improved: combine parameters, remove or simplify sections, add sections
- To identify data needs

Therefore SA helps to ascertain the areas of uncertainty that most affect management outcomes, making it essential for adaptive modelling.

Information and Decision Support Systems

Models can play a key role in decision making for environmental management and policy, by providing a means of formulating and exploring problems and bounding the range of uncertainty. Models can be used to discriminate and compare different options or strategies in a qualitative, if not, quantitative way, to assist in the selection of the 'optimal' alternative. The priorities and value judgments of decision makers can also be incorporated into the decision making process in a transparent manner.

There are some distinct advantages in performing integration methods within an appropriately-designed framework and tools where the audience and needs are well-identified for their prescription. They can constitute (Jakeman & Letcher, 2003):

a way of investigating tradeoffs and explaining them to interest groups; a readily accessible collection of models, methods and visualisation tools that can be updated; a focus for integration across researchers and stakeholders; a training and education function; an exploratory aid capable of adoption and further development by stakeholders; a permanent summary of the project methods; and a means of making the management analysis transparent.

An Illustrative Problem in Catchment Management

Here we provide an example of the development and application of a model to inform the process of adaptive management. The example is taken from a modelling-focused study of water quality in the catchments of the Eurobodalla region of southeastern NSW. The study was undertaken in a partnership between the Eurobodalla Shire Council, the NSW Department of Environment and Climate Change and the Australian National University. The objective was to identify high leverage management options for the control of sediment and nutrient inputs to streams, drinking water sources and estuaries. Such information is required to inform the adaptive management process whereby local managers seek knowledge of how their actions are expected to improve water quality.

The modelling is based around a Coupled Components model known as CatchMODS. CatchMODS combines hydrologic, sediment, nutrient and economic models in an integrated framework that is suitable for use by managers to test scenarios of alternative management. The model is constructed in accordance with the general principle of good modelling practice, evolving over an iterative cycle of application, evaluation and redevelopment within the study and as a legacy of previous investigations. In the Eurobodalla region, the model is constructed at a scale commensurate with the management objectives, available data and the level of existing process knowledge.

The structure and parameters of the model have been modified over the course of the study as process understanding and data become available. Driving this process are inputs from targeted scientific studies and monitoring programs. The initial steps in the modelling and assessment process for the Eurobodalla region were the identification of potential pollutant sources and the construction of coarse temporal and spatial scale hydrology and pollutant budgets. These early investigations enabled critical information and knowledge gaps to be identified and targeted. An important outcome was the establishment of an event-based water quality sampling program. The monitoring program enabled (i) identification of dominant pollutant generation process via interpretation of pollutant concentration and hydrograph data, and (ii) estimation of pollutant loadings. A lack of knowledge of pollutant inputs from intensive agriculture and from unsealed roads in the catchments led to the commissioning of a farm-scale nutrient budgeting study and to the application of measurement and modelling programs to estimate sediment yields from unsealed roads.

The information garnered from these studies was incorporated into the CatchMODS model. This was achieved in several ways including via improved estimates of parameter values, changes in the structure of the model where appropriate and the addition of new components of the model specifically for estimating sediment inputs from unsealed roads. Independent data to evaluate the effectiveness of the modelling was also sought ultimately to improve the modelling process and to inform the adaptive management cycle. In the study described here this was achieved via the comparison of model outputs against sediment tracing results at selected stream tributaries. SA techniques to investigate high leverage data gathering activities and more fully understand the behaviour of the model have been used in the study.

Through the iterative process described above the model produces relatively detailed spatial representations of pollutant sources. Importantly, estimates of the costs of implementing the various management scenarios that are tested are also available and provide valuable information to prioritise management effort.

The development and application of the model and its various supporting studies have all incorporated consultation to varying degrees with local experts, decision makers and the local community. The effect has been the development of a model that is appropriately focused, accepted by decision makers and is far more likely to produce management recommendations acceptable to the local community. The challenge remains to keep cycling through the adaptive management loop, using the model to inform continuing data collection and evaluation activities and to over time refine the underlying model. This has been at least partly achieved in the Eurobodalla case study but further progress is possible. It requires longer term research projects and a balance between data collection, evaluation, model development and consultative activities.

Coupling complex models are especially well-suited to problems where a small number of issues are being investigated (e.g., water allocation policy and environmental flows) and much detail is required spatiotemporally in terms of drivers, processes and impacts. Care needs to be taken in their direct use with a non-technical audience. But they can be hybridised with other approaches, such as Bayesian networks, to make their value more accessible.

Vegetation Management in a Conservation Reserve

Bayesian decision support tools are becoming increasingly popular as a modelling framework that can analyse complex problems, resolve controversies, and support future decision-making in an adaptive management framework. Traditionally, environmental management strategies have sought to avoid addressing uncertainty (Walters, 1997), leading to poor environmental outcomes and profound ecological and economic impacts (Halpern et al., 2006). Today, the importance of quantifying uncertainty in decision-making is being increasingly recognised as providing a mechanism for describing realistic outcomes, adding flexibility to the decision process, and dealing with variable systems, where our knowledge is poor or incomplete.

In representing and communicating our knowledge of complex systems, Bayesian networks are valuable aids. They are especially useful integration tools when there is strong connectivity among several issues and policies; for example, water allocation, supply, biodiversity, industrial production, social and cultural impacts. They also should be considered strongly in a planning context and/or when participation goes beyond technical interest groups and generation of trust and sharing of knowledge are quintessential. Because of their probabilistic nature they can represent uncertainties and can also be used in a risk assessment framework. Bayesian networks also can be updated when new information comes to light, or our understanding of a system changes.

A Bayesian network model was designed to assist in the management of an endangered Eucalypt species, the Swamp Gum (*Eucalyptus camphora*), found in the Yellingbo Nature Conservation Reserve (YNCR), an isolated patch of forest in the Yarra Valley (Victoria, Australia) (Pollino et al., 2007). The eucalypt community provides both habitat and food for a variety of threatened and endangered flora and fauna. Over the last 20 years the *E. camphora* has become increasingly threatened by dieback. In order to protect existing trees and encourage regeneration, management strategies and investments in restoration have focussed on restoring the hydrological regime, which has been altered due to agricultural activities within the catchment. However, there is still much debate on what the causal factors are resulting in dieback.

A Bayesian network model was constructed to integrate information on all the factors (Fig. 9.2) that were perceived by the scientists and reserve managers as affecting the eucalypt community (Pollino et al., 2007).

The model acted as an evidence base to better characterise the breadth of possible threatening processes affecting the eucalypt, and this was used to explore the strengths between the various hypotheses of the causal factors resulting in dieback. Using SA, we found that the key drivers in determining the condition of the eucalypt were strongly related to the group conducting the study in the reserve. Consequently, the drivers of eucalypt condition were biased by research group.

Unfortunately, given the poor quality of data and knowledge available, further research is required to definitively identify the causal factors of dieback. Instead the

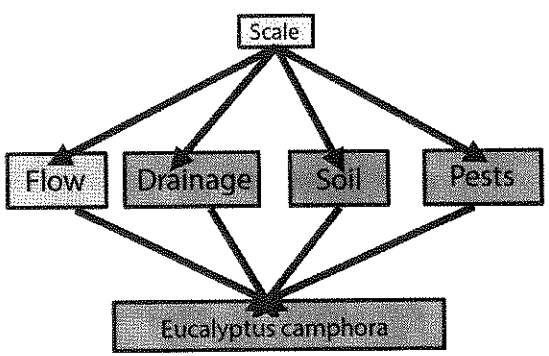

Fig. 9.2 Model schematic, where scale has two components: the locality in the conservation reserve and the group who conducted a study in the reserve

model acted as a demonstration of how important it was to undertake studies that were integrative, holistic and designed well. With future monitoring and research, the BN can be iteratively updated. This will inform and assist the development of future management strategies.

In the eucalypt study, assessment and management strategies had focussed on simplistic cause and effect hypotheses. Expensive interventions in the reserve had been undertaken based on this simple hypothesis, with little improvement in the condition of the eucalypt community. In focussing on a simple solution, it was evident that this had been to the detriment of the reserve. The BN approach offered a solution by addressing the need to better understand a complex system, while acknowledging the uncertainties that exist in our understanding of the functioning, and the variability that is inherent within systems.

As recognised by Walters (1997), although a wide range of alternative models can be equally 'valid' in ecology, they can also have wildly different predictions about the effects of various management policies. This inability to discriminate among alternative hypotheses based on historical data does not imply that modelling and analysis of historical data are useless exercises (Walters, 1997). Rather models should be used to direct more efficient field testing processes for further testing and evaluation.

At this stage, more efforts in generating alternative or additional models and hypotheses about dieback of *E. camphora* would be unproductive and a wasteful expenditure of limited resources and effort. What is needed is robust and systematic collection of further (new) data, routine analysis of data, and responsive management plans. BNs, and more generally Bayes' theorem, can provide a framework for the efficient accumulation and use of such evidence (Newman & Evans, 2002) to formulate improved and adaptive management strategies.

Barriers to Modelling for Adaptive Management

The high complexity of environmental problems, and the dynamic and poorly understood nature of many system processes, mean that no model can be perfect. Typically, models are specific to the dataset used to calibrate the input parameters, and thus are not necessarily transferable to other sites or time periods. There are also technical issues related to spatial and temporal cross-scale linkages between physical, chemical and biological processes (Walters, 1997). For example, change takes time to manifest itself especially in ecological systems, making it difficult to monitor let alone model the processes. Although these limitations must be appreciated, they should not discount the value of models in adaptive management, as the alternative is a less disciplined and accountable process.

In addition to adhering to standards, the education of modellers on further aspects is warranted; for instance, on how to engage with clients and stakeholders, on the need to develop more flexible models and on understanding the context in which the model will be used. The perceived credibility and accessibility of

models by stakeholders and end-users such as managers can pose a barrier to their use. This challenge can be overcome through conforming to the good modelling practice protocols mentioned above and collaborative working between modellers, stakeholders and end-users, which can also help ensure that the model is built for the right purpose and used appropriately.

The development of long-term partnerships between modellers and model end-users is fundamental to promoting ongoing adaptive management. If trust is built between the two groups and the broad problem issues being addressed are ones of continuing concern (e.g. ecosystem health), then it is likely that funding sources for the collaborative efforts in improving management outcomes can be identified. Even as sources and topics for funding change, ways can often be found to reorient the work to capture such funding. Pursuing robustness in the relationships should be a major aim, making sure that it is not dependent on one individual champion.

Integrated assessment is becoming increasingly accepted and applied to inform environmental decision making. As an iterative and inclusive process focussed on better sustainability outcomes, it has much in common with adaptive management. IA exercises promote engagement by stakeholders, systems thinking and transparency, which can only assist people in appreciating one another's perspectives. Put crudely, adaptive management would benefit more from IA's principles, while IA would benefit from an adaptive management focus that uses models, analytic tools and processes that accelerate or increase our understanding and management of a system for the long term.

Conclusions

- Modelling is an important tool for adaptive management. It can assist communication, identifying knowledge gaps and prioritizing management options and monitoring requirements.
- Selection of a modelling approach must be purposeful and targeted to the issues, stakeholders and users.
- Approaches to modelling fall along a continuum that ranges from expert/reductionist/specialist to participatory/multidisciplinary/systems focused.
- Each modelling approach has capabilities and limitations, which must be appreciated if the tool is to be used effectively.
- Stakeholder participation, and preferably partnerships, throughout the modelling process can be an effective means of sharing and communicating knowledge and values, thereby enhancing the success of adaptive management.
- Models will always need adapting to the context of the given task/problem.

References

Costanza, R. and Ruth, M. (1998). Using dynamic modeling to scope environmental problems and build consensus. *Environmental Management* 22(2): 183–195.

Field, S.A., O'Connor, P.J., Tyre, A.J. and Possingham, H.P. (2007). Making monitoring meaningful. *Austral Ecology*, 32: 485–491.

Forsyth, R. (1984). The expert systems phenomenon. In: Forsyth, R. (Ed.), *Expert Systems: Principles and Case Studies*. Chapman & Hall, London, pp. 3–8.

Halpern, B.S., Regan, H.M., Possingham, H.P. and McCarthy, M.A. (2006). Accounting for uncertainty in marine reserve design. *Ecology Letters* 9: 2–11.

Hare, M., Letcher, R.A. and Jakeman, A.J. (2003). Participatory modelling in natural resource management: A comparison of four case studies. *Integrated Assessment*, 4: 62–72.

Jakeman, A.J. and Letcher, R.A. (2003). Integrated assessment and modelling: Features, principles and examples for catchment management. *Environmental Modelling and Software*, 18: 491–501.

Jakeman, A.J., Letcher, R.A. and Norton, J.P. (2006). Ten iterative steps in development and evaluation of environmental models. *Environmental Modelling and Software*, 21: 602–614.

Jakeman, A.J., Letcher, R.A. and Chen, S. (2007). Integrated assessment of impacts of policy and water allocation change across social, economic and environmental dimensions. In: Hussey, K. and Dovers, S. (Eds.), *Managing Water for Australia: The Social and Institutional Challenges*. Melbourne: CSIRO, pp. 97–112.

Letcher, R.A. and Jakeman, A.J. (2003). Application of an adaptive method for integrated assessment of water allocation issues in the Namoi river catchment, Australia. *Integrated Assessment*, 4: 73–89.

McLain, R.J. and Lee, R.G. (1996). Adaptive management: Promises and pitfalls. *Environmental Management*, 20(4): 437–448.

Newham, L.T.H., Jakeman, A.J. and Letcher, R.A. (2006). Stakeholder participation in modelling for integrated catchment assessment and management: An Australian case study. *International Journal of River Basin Management*, 4(3): 1–13.

Newman, M.C. and Evans, D.A. (2002). Enhancing Belief during Causality Assessments: Cognitive Idols or Bayes's Theorem. In: Roberts, J.M.H., Newman, M.C. and Hale, R.C. (Eds.) Overview of Ecological Risk Assessment in Coastal and Estuarine Environments. Lewis Publishers, New York, USA, pp. 73–96.

Pollino, C.A., White, A.K. and Hart, B.T. (2007). Examination of conflicts and improved strategies for the management of an endangered Eucalypt species using Bayesian networks. *Ecological Modelling*, 201: 37–59.

Rivers-Moore, N.A. and Jewitt, G.P.W. (2007). Adaptive management and water temperature variability within a South African river system: What are the management options? *Journal of Environmental Management*, 82: 39–50.

Saltelli, A. Chan, K. and Scott, E.M. (Eds.) (2000). *Sensitivity Analysis*. Wiley, Chichester, 475pp.

Sutherland, W.J. (2006). Predicting the ecological consequences of environmental change: A review of methods. *Journal of Applied Ecology*, 43: 599–616.

Tickhurst, J. (2008). Evolution of an approach to integrated adaptive management: The Coastal Lake assessment and management (CLAM) tool. *Ocean and Coastal Management*, 51: 645–658.

Tickhurst, J.L., Newham, L.T.H., Rissik, D., Letcher, R.A. and Jakeman, A.J. (2007). A Bayesian network approach to assess the sustainability of coastal lakes. *Environmental Modelling and Software*, 22: 1129–1139.

Walters, C. (1997). Challenges in adaptive management of riparian and coastal ecosystems. *Conservation Ecology*, 1(2): 1 [online] URL: http:// www.consecol.org/vol1/iss2/art1/.

Walters, C., Korman, J., Stevens, L.E. and Gold, B. (2000). Ecosystem modeling for evaluation of adaptive management policies in the Grand Canyon. *Conservation Ecology*, 4(2): 1 [online] URL: http://www.consecol.org/vol4/iss2/art1/.