Decision Analysis/Adaptive Management (DAAM) for Great Lakes fisheries: a general review and proposal

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Comments and questions on this draft discussion paper are requested and would be greatly appreciated by the authors

Table of contents

1. Introduction

The local history of DAAM in Great Lakes fisheries management goes back to early 1990s. Not long after a 1993 court decision (*R. v. Jones-Nadjiwon* (1993) reaffirmed the Aboriginal and Treaty rights of the Saugeen Ojibway (comprised of Saugeen First Nation and the Chippewas of Nawash Unceded First Nation), Nawash released a biological review and evaluation of the OMNR Lake Huron commercial fisheries management program. This report identified the need for a stronger emphasis in Lake Huron fisheries management on science-based processes that are incorporated into Adaptive Management (AM) (Crawford 1996). Over the next several years, Nawash continued to develop the application of AM for commercial fisheries management in the Great Lakes generally, and for those in Lake Huron specifically (Morrison & Crawford 1999, Crawford & Morrison 1999a, Crawford & Morrison 1999b, Crawford et al. 2001, Crawford et al. 2003).

AM was proposed by Nawash for consideration at the Saugeen Ojibway / Canada / Ontario Plenary during negotiations leading to the 2000 Fishing Agreement. During the term of the Fishing Agreement, the Ontario Ministry of Natural Resources proposed the use of the principles of Decision Analysis (DA), as proposed for the walleye (*Sander vitreus*) and yellow perch (*Perca flavescens*) fisheries by the Lake Erie Committee of the Great Lakes Fishery Commission. The Plenary recognized the great potential for explicitly combining principles of DA and AM for their fisheries management issues. In February 2003, the Saugeen Ojibway/Canada/Ontario Plenary convened a special meeting to consider presentations on DA and AM by two experts in the field: Prof. Mike Jones (Michigan State University) and Prof. Tom Nudds (University of Guelph). The discussions at this special meeting led to the collaborative development of a set of 'Draft Principles for DAAM' (Jones & Nudds 2003), Appendix I). The Saugeen Ojibway and Ontario committed to further exploring DAAM as a basis for future discussions of Lake Huron fisheries resource management issues. The Ontario Ministry of Natural Resources hosted a multi-stakeholder workshop on DAAM in Port Elgin in May 2003, at which a general consensus was reached among attendees on the need for DAAM in Lake Huron fisheries management.

Discussions between Nawash, the University of Guelph, and the Ontario Commercial Fisheries' Association have led to an agreement among the partners to collaborate in a Graduate and Post-Doctoral research program to explore the theoretical and applied issues of combining DA and AM, using commercial fisheries on Lakes Erie and Huron as case studies (Nudds et al. 2003). As part of the preliminary scope of work developed for the DAAM Project, the partners agreed to undertake a review of primary and technical scientific literature on DAAM in fisheries science and management. This document represents the <u>first draft</u> of that review, which is being distributed for consideration and comment by fishermen, ecologists, managers and anyone with an interest in Great Lakes fisheries management.

Goals of this review

The general goals of this review can be stated as follows:

1. Review the principles and linkages of DA and AM;
2. Explore options for a management system that would increase transparency/accountability and reduce conflict among governments, agencies and stakeholders; and
3. Propose a practical template for DAAM in resource management generally, and Great Lakes fisheries management specifically.

We have attempted to follow the excellent advise offered by Morgan & Henrion (1990) in their ‘Ten commandments’ for good policy analysis (Appendix II) in the preparation of this review, especially: (1) Do your homework with literature, experts, and users; (2) Let the problem drive the analysis, and (10) Expose the work to peer review. We are hopeful that the reader will find this draft report to be a useful step toward the development of science-based management for Great Lakes fisheries.

2. Adaptive Management (AM)

"*Adaptive management is not really much more than common sense.
But common sense is not always in common use.*" (Holling 1978)

Adaptive management (AM) is all about learning (i.e. reducing key uncertainties through management). It is designed to identify and address key uncertainties about resource dynamics, and to iteratively use feedback information from the system being managed to reduce those key uncertainties (Walters 1986). Key uncertainties can be associated with management objectives (socio-bio-economic), with data (observational), or with models (structural) that we create to help us describe and understand the interactions between the various components of the system (Lee 1993, Peterman & Peters 1998, Anderson et al. 2003). From a management perspective, AM can provide information to managers on "*what works and what does not work*" (Stolnack et al. 2005). In this sense, every key uncertainty in management is a learning opportunity (Grumbine 1994, Murray & Marmorek 2003b).

In AM, management actions are regarded as treatments that can be intentionally implemented to help distinguish between alternative hypotheses about how the world works (Hilborn & Walters 1992). The consequences of management actions on the supporting system can be measured as they relate to management objectives – which in turn, can be eliminated or revised to better match the nature of the ecological system and the objectives of managers and stakeholders (Horsten & Kirkegaard 2000, Schreiber et al. 2004).

In its many forms, AM has become recognized internationally as a very important tool for dealing with complex and valuable resource management systems (Horsten & Kirkegaard 2000, Holling 2004). Despite early difficulties in getting managers, harvesters and scientists to communicate effectively about AM, it has gradually gained acceptance as a reliable way of practicing science-based management decision making (Mee 2005). There are a variety of management conditions that lead people to consider using AM, including:

- Multiple competing management objectives;
- Complex and uncertain cause/effect relationships;
- Limited assessment and management resources; and
- Multiple individuals and/or organizations responsible and accountable for outcomes.

AM has been listed as one of the nine candidate criteria for sustainable and responsible fisheries (Pitcher 2004, 2005). One of the largest scale examples of an adaptive management project was the flooding of the Grand Canyon to restore flow features that had been disrupted by the construction of the Glen Canyon Dam, upstream on the Colorado River (e.g. USGS 1998). AM has also been directly incorporated into a variety of management policies, including NOAA implementation of the precautionary principle in US marine fisheries (Gable

2004), forest planning by the USDA Forest Service (Stolnack et al. 2005), river management planning by the Nature Conservancy (Richter et al. 2003), and a host of other resource management applications (Wall 2003).

Despite the recent increase in AM application, it still remains a frequently misunderstood management tool (Schreiber et al. 2004). Part of the reason for this confusion is that AM is easy to understand – almost (Lee 1993). In other cases, managers have unintentionally increased confusion by mistakenly applying the label 'AM' to management systems which do not implement the fundamental requirements (Wall 2003, Wheaton et al. 2004a). Murray & Marmorek (2003) identified the following common misconceptions that AM is:

- Trial-and-error;
- Spurious adaptation of policies as you go;
- Sophisticated modelling skills and tools;
- Consensus from all stakeholders;
- Something scientists do; and
- A panacea that can solve all problems.

In other cases, bona fide AM has emerged as a significant concept for discussion, yet practitioners have been unable to find a way to actually implement it (Lee 1999, Riley et al. 2003).

One of the fundamental challenges in dealing with resource managers is a fundamental fear of admitting that there are many aspects of the ecosystem and effects of resource use that everyone (including the managers) is uncertain about. If resource managers can work with scientists and stakeholders to confront this fear of admitting uncertainty, then all parties can begin to focus on the real job at hand – developing effective tools for explicitly reducing the key uncertainties (i.e. learning) in the future. Reducing uncertainty in this way should allow managers to make a better decision than would have been possible in the absence of AM.

Policy as Hypothesis, Management by Experiment

In the early 1990s, AM practitioners developed an effective tool for engaging resource managers in a discussion about how priorities for policy-driven processes were actually a form of the scientific method. Lee (1993) urged managers to see "policies as experiments: learn from them." This analogy between policy evolution and the scientific method has been termed 'Policy as Hypothesis, Management as Experiment' (Lancia et al. 1996). In 1996, Holling noted that in AM, policies are designed as hypotheses and management implemented as experiments to test those hypotheses with consequences of the (management) actions potentially reversible, and that the experimenter learns from the experiment. Nudds (1999) and Wiersma (2005) have shown that management policies can be implemented in an experimental context that improves understanding of the policy and effects, in the same way that confidence in scientific hypotheses (possible cause and effect mechanisms) is updated by the generation of predictions from the hypotheses, and then testing those predictions (Figure 1).

Origin and Development of AM

At this point it would be helpful to take a brief look at the conceptual history of AM in the scientific literature. Numerous reviews and evaluations of AM have been published on this topic (e.g. (Holling 1978, Walters 1986, Hilborn & Walters 1992, Lee 1993, Gunderson et al. 1995, Lancia et al. 1996, Walters 1997, Parma et al. 1998, Johnson 1999, Grafton & Kompas 2004, Schreiber et al. 2004, Walters & Martell 2004).

For the purpose of this section, we have selected a few examples that we believe are noteworthy in the technical history of AM, or serve to demonstrate a trend of AM becoming more explicit in structure, function and execution. We value Holling's (1978) argument that such examples of AM serve to give the reader a sense of the order of events, rather than suggesting that development has led to some perfect "recipe" – a highly prescriptive process would be exactly the opposite of what AM is intended to create.

In 1978, C.S. (Buzz) Holling edited a volume entitled "*Adaptive Environmental Assessment and Management*" (AEAM) in which a group of colleagues[1] first synthesized the concepts of AM in a broad, coordinated manner. Co-authors Walters & Hilborn (1976, 1978) had actually published a specific form of adaptive management to the fisheries literature just prior to Holling (1978). However, it appears from the acknowledgements of Holling (1978) that there were few, if any, conceptual divisions between AM colleagues in those days. The authors perceived their work as a targeted response to their realization that natural resources were more limited than previously considered. If these resources were to continue providing sustainable benefits then people were going to require a new way of dealing with uncertainties in their understanding of the ecological systems, and the possible consequences or human use (Holling 2004). In this earliest state, AM took the form of 'hands-on' examples and case demonstrations; however there really was no formalized step-wise account of the AEAM technique (notwithstanding the title of Chapter 3 "Steps in the Process"). This lack of formalization did not prevent managers and scientists from recognizing the great value in the Holling (1978) compilation – it became widely cited as the source for this way of thinking, and the term AEAM became synonymous with AM (Schreiber et al. 2004).

[1] The names of Holling's (1978) international co-authors are often overlooked when this important text is cited. They included: Alexander Bazykin, Pille Bunnell, William C. Clark, Gilberto C. Gallopin, Jack Gross, Ray Hilborn, Dixon D. Jones, Randall M. Peterman, Jorge B. Rabinovich, John H. Steele, and Carl J. Walters.

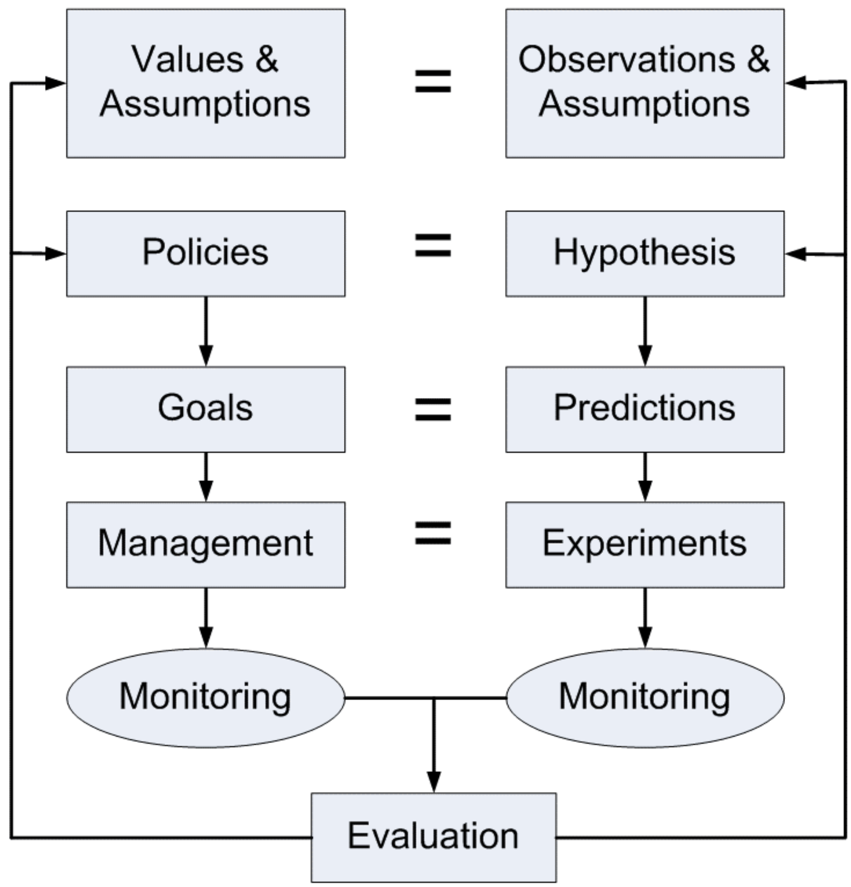

Figure 1. "Policy as Hypothesis, Management as Experiment." A framework for Adaptive Management (from the Panel on the Ecological Integrity of Canada's National Parks Report 2000; pg. 3-2 – adapted from Wiersma 2005, Nudds 1999, Holling 1996). In this approach resource managers test their policies with management actions, reducing key uncertainties about the ecological/human system in a science-based manner.

In 1986, Carl Walters published his seminal volume entitled "*Adaptive Management of Renewable Resources,*" in which he laid out a more structured description and discussion of what AM really was, and how it could be formalized in a manner that worked for both quantitative analysts, ecological researchers and policy-oriented managers. In particular, Walters (1986) stressed the importance of stakeholder consultation, design, dealing with prior information, probabilities of competing hypotheses, and explicit reduction of key uncertainties. Of particularly importance to this review is the fact that Walters (1986) offered the first step-wise account of AM:

> "*The business of designing adaptive management strategies appears to involve four basic issues:*
>
> 1. *Bounding of management problems in terms of explicit and hidden objectives, practical constraints on action, and the breadth of factors considered in policy analysis;*
> 2. *Representation of existing understanding of managed systems in terms of more explicit models of dynamic behavior, that spell out assumptions and predictions clearly enough so that errors can be detected and used as a basis for further learning;*
> 3. *Representation of uncertainty and its propagation through time in relation to management actions, using statistical measures and imaginative identification of alternative hypotheses (models) that are consistent with experience but might point toward opportunities for improved productivity;*
> 4. *Design of balanced policies that provide for continuing resource production while simultaneously probing for better understanding and untested opportunity.*" Walters (1986), p.8)

These were the seeds of formal technique to which a large number of AM practitioners would trace the history of their thinking about AM.

AM Cycles

At some point in the 1990s, AM practitioners began to communicate their understanding of the technique in terms of a 4-step adaptive management cycle, that focused on Review, Plan, Implement and Monitor (Figure 2). While the origins of this cyclical representation are obscure, it appears that it may have been related to management planning that crossed disciplinary boundaries from economics/business schools. For example, Kotler (1991) presented something very similar - referred to as a management cycle - with iterative steps identified as Analysis, Planning, Implementation and Control (Bosch et al. 2003, Smith & Bosch 2004). Regardless of the specific origin of the 4-step AM cycle, it is a noteworthy progression from Walters' (1986) progression in one major respect – it stresses the iterative nature of a learning tool, in contrast to a linear system with little or no feedback (Murray & Marmorek 2003). The same kind of 4-step cycle has also been referred to as the 'passive adaptive management cycle' (Hilborn 1996) in the iterative form:

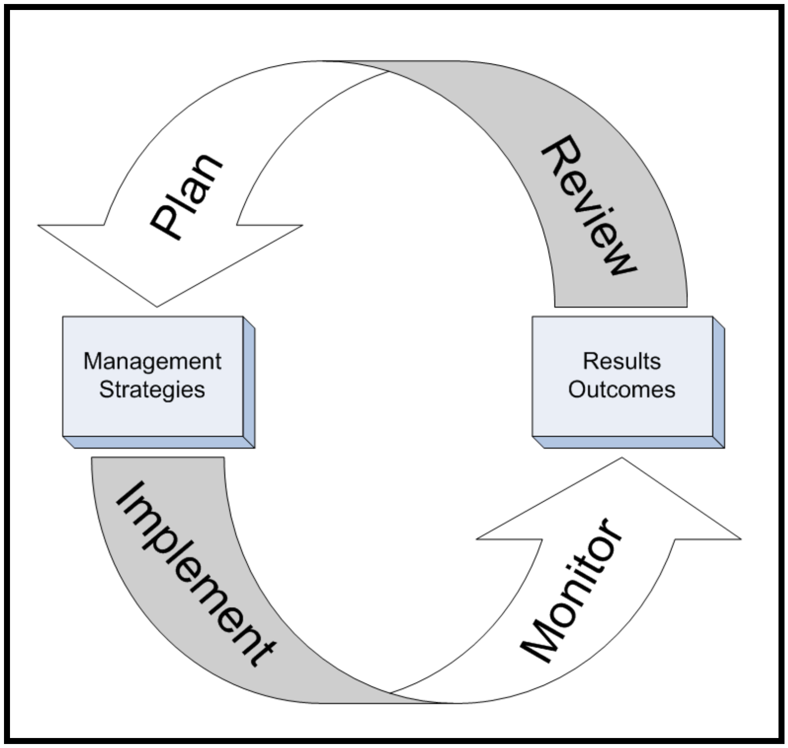

Figure 2. A 4-step approach to the cycle of Adaptive Management (AM) in which the process iterates from Review of information, to Planning of management strategies, through Implementation of the strategies and Monitoring of predicted effects (Bosch et al., 2003; Smith & Bosch 2004). While this 4-step cycle does not provide much detail on how AM would actually be done, it does stress the iterative nature of a learning tool, in contrast to a linear system with little or no feedback.

1. Define alternative models;
2. Evaluate alternative actions;
3. Implement management plan;
4. Evaluate outcomes.

In this case, the essential AM features combine the features of multiple states of nature and multiple hypotheses, although it appears that only single management objectives were recognized.

Over time, several variations emerged on the 4-step AM cycle, including extensions by Hilborn & Walters (1992):

1. Identify alternative hypotheses or models of the resource;
2. Assess whether further steps are necessary by estimating the expected value of perfect information, EVPI;
3. Develop baseline policies;
4. Develop adaptive, probing policy options;
5. Develop performance criteria to measure success;
6. Compare options.

This AM approach introduces new concepts and associated terminology (e.g. expected value of perfect information (EVPI), adaptive probing policies), and reflects the idea that management objectives needed to become a more important part of the formal process. Recently, Grafton & Kompas (2004); applied 6 steps specifically for AM in the design of marine reserves:

1. Prioritise and quantify management goals;
2. Socio-economic-ecological system appraisal;
3. Choose & apply ecological & socio-economic criteria;
4. Determine management options;
5. Stakeholder & peer review;
6. Active learning, experimentation & evaluation.

In this case, the socio-economic aspects of AM are more heavily emphasized, with experimentation and learning identified mostly in the final step.

6-Step AM Cycle

"*A spoonful of rigour helps the uncertainty go down*" (Murray & Marmorek 2004b)

For the purposes of this review, we have selected a particular version of the AM cycle that has flourished over the past decade. The 6-step AM cycle emerged from a combination of efforts related to the BC Forest Service and work of professional environmental consultants at ESSA Technologies (Murray & Marmorek 2003, 2003b). In its simplest form, this 6-step AM cycle takes the form of a graphic (Figure 3) that identifies the following steps in an iterative cycle:

1. Assess;
2. Design;
3. Implement;
4. Monitor;
5. Evaluate;
6. Adjust

This simple 6-step AM cycle is set somewhat apart from its predecessors by the fact that it is associated with a more detailed description of specific AM tasks. Consider the following step-wise description, paraphrased from (Murray & Marmorek 2003):

Step 1: Assess (Define)

The first step involves clearly defining and bounding the problem. This includes identifying management objectives, as derived from the input of all stakeholders, carefully focusing on fundamental objectives, or what you want, rather than means objectives, or how to get it. The analyst must identify possible suites of actions that could be taken to achieve objectives, clear indicators or performance measures that could be monitored to determine whether the actions are indeed achieving desired objectives. Key uncertainties in the system must be scoped, especially as they relate to competing hypotheses about ecosystem structure/function (i.e. states of nature), and how proposed management options are predicted by the hypotheses to affect the indicators or response.

Step 2: Design

The second step involves designing a management plan that details the specific actions that will be taken toward testing predictions generated by the competing hypotheses regarding the key uncertainties identified in Step 1. The management plan should contain sufficient detail to properly carry out all prescribed activities. This step also includes the preparation of a detailed monitoring plan, specifying sampling design, scale, variables, and methods. Sampling design should be sufficient to detect effects that are environmentally important, given the natural variation in indicators over time and space.

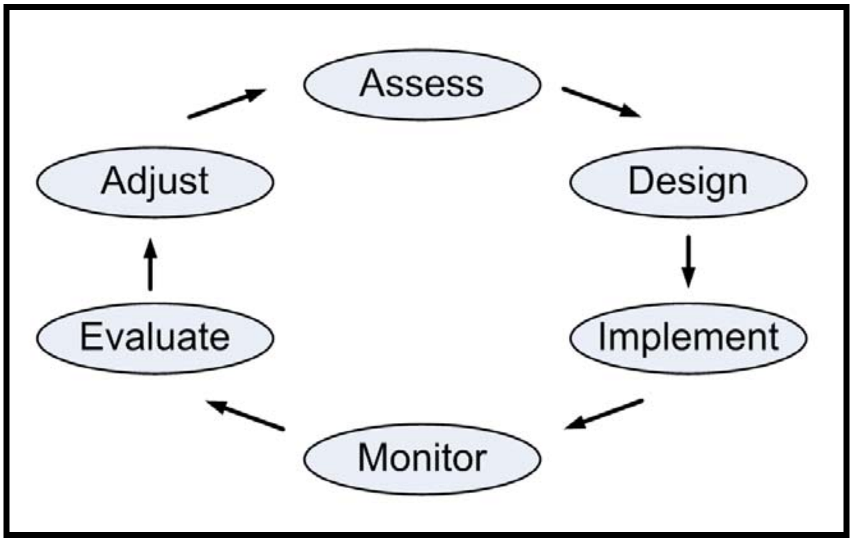

Figure 3. A 6-step Adaptive Management (AM) cycle presented by Nyberg (1999) in the Proceedings Ontario Ministry of Natural Resource Adaptive Management Forum (MacDonald et al. 1999). In this approach, steps in the cycle are refined in terms of how they relate to management objectives, competing hypotheses, management experiments and learning.

Step 3: Implement

The third step comprises implementation of the management plan. It is critically important that practitioners understand the logic of the experimental design. All aspects of the plan must be adhered to. Deviations in the implementation plan for unavoidable operational reasons can be expected under many field conditions. Such deviations and their rationale must be clearly documented.

Step 4: Monitor

The fourth step constitutes the monitoring component, which in turn is comprised of three aspects: (a) monitoring implementation to ensure that activities were undertaken as prescribed, (b) monitoring indicators to learn whether the activities worked, or achieved the original objectives, and (c) monitoring indicators to test alternative hypotheses for key uncertainties.

Step 5: Evaluate

The fifth step involves analyzing the monitoring data to learn what happened, and to compare the results with the hypotheses and their predictions, This step focuses on discovering whether predicted outcomes were accurate, and on learning which activities best achieve desired objectives.

Step 6: Adjust (Revise)

The final step in 'closing the loop' of the AM cycle is the revision of management objectives/policies, indicators, uncertainties and hypotheses, based on what was learned during the previous cycle.

A refined version of this 6-step AM cycle, presented by Murray & Marmorek (2004b) is shown in Figure 4. In this case, the authors have taken the same basic design as previously shown, changed a few step names for clarification (Assess → Define, Adjust → Revise), and added brief step explanations on the graphic for ease of understanding. In our opinion, this graphic representation of the 6-step AM cycle and tasks described above, combine to form one of the most efficient and effective descriptions of AM technique that we found in our review. The terminology has become more focused on the specific importance of management objectives, key uncertainties, competing (alternative) hypotheses of cause-effect mechanisms, predictions generated by hypotheses, tests of the predictions, and the updating of probabilities for the competing hypotheses (i.e. learning).

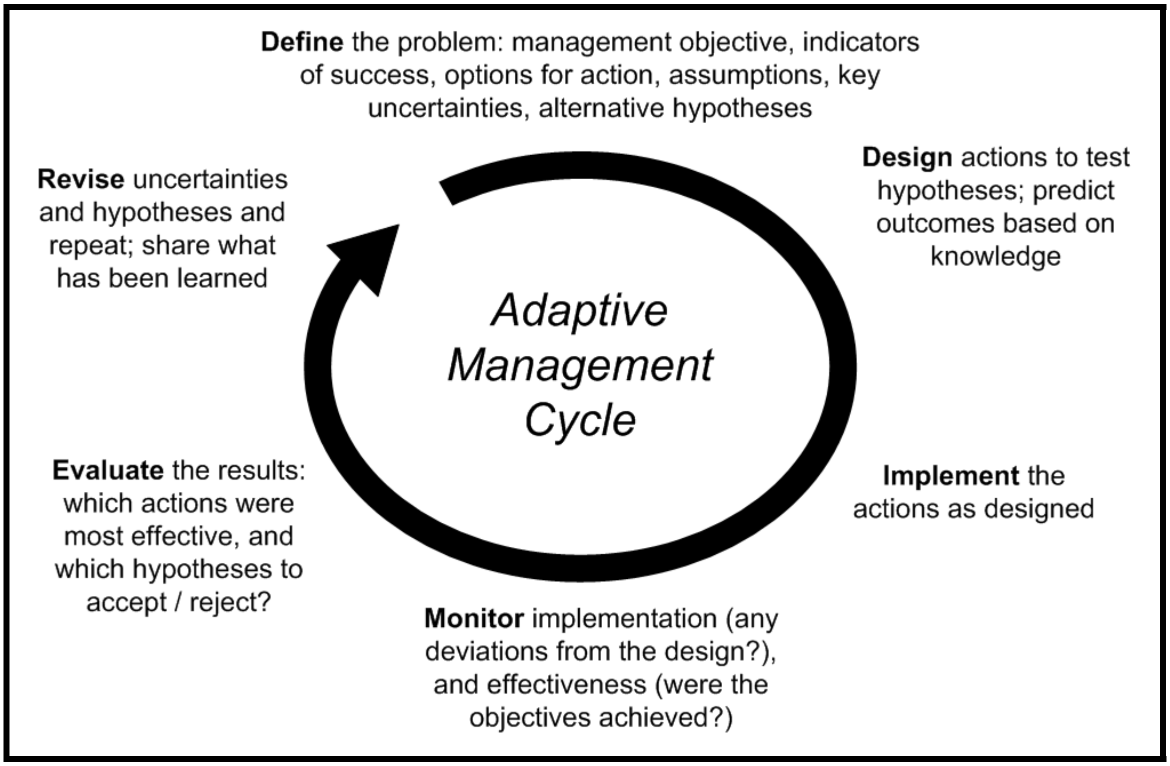

Figure 4. A refinement on the 6-step Adaptive Management (AM) cycle presented by Murray & Marmorek (2004b), where terminology has become more focused on the specific importance of management objectives, key uncertainties, competing (alternative) hypotheses of cause-effect mechanisms, predictions generated by hypotheses, tests of the predictions, and the updating of probabilities for the competing hypotheses (i.e. learning).

3. Decision Analysis (DA)

decide, *v.i.* “*To succumb to the preponderance of one set of influences over another set.*” (The Devil’s Dictionary, Ambrose Bierce, 1911)

Decision analysis (DA) focuses on the process of risk management (=making hard decisions in the face of uncertainty). The approach that resource management agencies have traditionally used to make decisions can be described by the means taken to quantify their uncertainties. As with AM (see above) pervasive uncertainties arise from ecosystem complexity, variability (natural and human-induced), sampling error, and structural (model) error (Peterman & Peters 1998). The degree to which uncertainty is explicitly treated in the decision-making process corresponds to the degree of quantification of the uncertainties (Peterman & Peters 1998). Peterman & Anderson (1999) described five ways that resource managers have historically addressed uncertainties:

1. Best point estimates for parameters and state variables that describe the system state and dynamics This approach effectively ignores uncertainties because they are not taken into account after the parameters are estimated;
2. Maintaining the status quo (when agencies are reluctant to change their policies because outcomes of actions are very uncertain);
3. Aggressive policies for harvesting when pressures are high for large, short-term economic yields and the potential negative consequences cannot be convincingly demonstrated;
4. Application of somewhat arbitrary safety margins, such as 20% to 50% reductions in harvest rates of fish populations, or other precautionary actions (when risks are assumed to be high); and
5. Explicitly and quantitatively consider the implications of uncertainties for decisions – that is, decision analysis.

Qualitative approaches may crudely consider uncertainty, but only in part, as selected by decision-makers, and can thus be used to justify virtually any decision (Peterman & Peters 1998). In contrast, quantitative approaches to decision-making, unambiguously reduce the arbitrariness in decision-making, by explicitly incorporating risk and uncertainty into the evaluation of decision alternatives, and maximize the probability of choosing the most beneficial option with the lowest losses (Raiffa 1968, Lindley 1971, Keeney & Raiffa 1976, McAllister & Peterman 1992b).

In decision-analytic terms, a loss is defined as an “*undesirable outcome of a decision*” (Peterman & Peters 1998), whereas risk can be described as the weighted average loss weighted by its probability of occurrence (Morgan & Henrion 1990, Peterman & Peters 1998, Peterman & Anderson 1999). In other words, risk is identified in the broadest sense as expected losses from any particular action (Peterman & Anderson 1999). The economic uncertainties confronted in these applications can be compared to ecological uncertainties in the management of natural resources (Peterman & Peters 1998). These include multiple stakeholders with varied objectives, an operating system that is difficult to predict, stochastic and uncontrollable variables, and a resource of significant value.

DA is a specific form of decision-making that explicitly takes into account key uncertainties as quantitative variables in order to evaluate the effects of various management options (Morgan & Henrion 1990, Peters & Marmorek 2001). DA is based on the idea of using several competing hypotheses about the 'states of nature' to describe the condition of the world. These variable conditions lead to the recognition of different possible outcomes for each management option being considered (Peterman & Anderson 1999). At the very least, DA allows for complex problems to be reduced to smaller more manageable components which can be re-assembled after analysis (Peterman & Peters 1998). At a higher level, DA also provides the ability to rank management options on the basis of stakeholder satisfaction, expected value, and ultimately to determine the management option that has the best overall performance, over a range of hypothesized responses to management actions (Peters & Marmorek 2001).

Origin and Development of DA

The origins of DA can be traced to the early 18th century work of Johann Bernoulli, Thomas Bayes and Abraham de Moivre. Bernoulli was interested in explaining why people do not follow expected value models (i.e. expected utility models) when choosing among gambles, Bayes was interested in the revision of probability based on observations (Bayes' Theorem), while de Moivre developed the relative frequency concept of probability (Skinner 2001, Smith & von Winterfeldt 2004).

These early concepts survived at relatively obscure levels until von Neumann & Morgenstern (1947) published "*Theory of Games and Economic Behavior*" in which they laid the foundation for modern decision analysis by formally exploring the concepts of risk and utility (Smith & von Winterfeldt 2004). In 1954, Savage published "*The Foundation of Statistics*" in which he built upon the work of von Neumann & Moregenstern and others, to devise a system in which he combined utility theory from economics, and subjective probability theory from statistics.

Beginning in the late-1950s, a series of seminal works combined to firmly establish DA as a mature body of thought in management research and application:

- Robert Schlaifer (1959) "*Probability and Statistics for Business Decisions*"
- John Pratt, Howard Raiffa & Robert Schlaifer (1964) "*The foundations of decision under uncertainty: an elementary exposition.*"
- Howard Raiffa (1968) "*Decision Analysis: Introductory Lectures on Choices Under Uncertainty*"
- Howard Raiffa & Robert Schlaifer (1968) "*Applied Statistical Decision Theory*"
- Robert Schlaifer (1969) "*Analysis of Decisions Under Uncertainty*"
- Dennis Lindley (1971) "*Making Decisions*"
- Ralph Keeney and Howard Raiffa (1976) "*Decisions with Multiple Objectives: Preferences and Value Tradeoffs*"

According to Smith & von Winterfeldt (2004), it was Ronald Howard who was first to use the term 'decision analysis' in his (1966) paper "*Decision Analysis: Applied Decision Theory,*" and it was Howard (1968) who was the first to lay out a process he called the "decision analysis cycle" for dealing with specific decision problems.

Based largely on this explosion of DA research and application, research economists applied decision theory to a wide variety of applications in business, management and engineering, including: decision trees and investment theory (Magee 1964a, 1964b), risk aversion (Pratt 1964), managing risk and utility (Swalm 1966), role of preference in decision-making (Hammond 1967, Eilon 1969). By the 1970's DA was still considered by some to be an 'experimental' or 'untested' management technique, yet proponents were highly confidant that it would become an essential tool for systematically making decisions in the presence of uncertainty (Ulvila & Brown 1982). Currently, DA is widely recognized as one of the major platforms in economic research and business and management planning. In a 1954-2003 sample of management science primary literature, Smith & von Winterfeldt (2004) reported that 17% of the 'most-cited' articles were DA papers. Modern researchers enjoy a wealth of theoretical and applied references on DA, which has gained widespread acceptance in large corporations and government agencies (Ulvila & Brown 1982).

DA Cycles

An early example of an informal DA cycle in fisheries management can be found in Powers et al. (1975), where the authors presented a simplified decision-making model to generate, evaluate, rank and implement optimal strategies for a recreational fishery (Figure 5):

1. Selecting objectives
2. Are objectives met? (feedback)
3. Survey alternative strategies
4. Evaluation of alternative strategies
5. Are objectives reachable? (feedback)
6. Implement the "best" Strategy

In this case, unsatisfied management objectives trigger the development of alternate management strategies, which in turn are evaluated and ranked to determine the 'best' strategy. It should be noted that a feedback loop exists for returning the analyst through the cycle, if the management objectives were not 'reachable.' It is also interesting to note that Powers et al. (1975) made specific reference to the origin of this simple DA approach:

> "*The conceptual model (illustrated in Fig. 1) is not an original idea since it is followed implicitly by most decision-makers, but it is rarely formally defined. By defining the process explicitly, we can discover the areas in which we lack methods or information and determine if computer science and/or systems analysis can fill this gap.*" (Powers et al. 1975)

Thus, it can be seen that there was a movement toward becoming more explicit in the analysis of fisheries management decisions by the 1970s – following the major theoretical and corporate developments in DA during the 1950s and 1960s, as described in the previous subsection.

For the purposes of logical progression, consider a DA cycle (Figure 6) that was presented by Clemens & Reilly (2001) in "*Making Hard Decisions*," a text that has become a standard DA reference in modern resource management. This 'process flowchart' is characterized by seven steps:

1. Identify the decision situation and understand objectives;
2. Identify alternatives;
3. Decompose and model the problem (structure, uncertainty, preferences);
4. Choose the best alternative;
5. Sensitivity analysis;
6. Is further analysis needed? (feedback);
7. Implement the chosen alternative.

It should be noted that this DA cycle has a feedback loop incorporated directly within the process, and an important role for management objectives and alternative actions (hypotheses). Sensitivity analysis is included as a critical component, prior to the selection of a particular management option. This cycle also incorporates the concepts of certainty equivalence, utility, risk tolerance and risk scaling via the model of preferences.

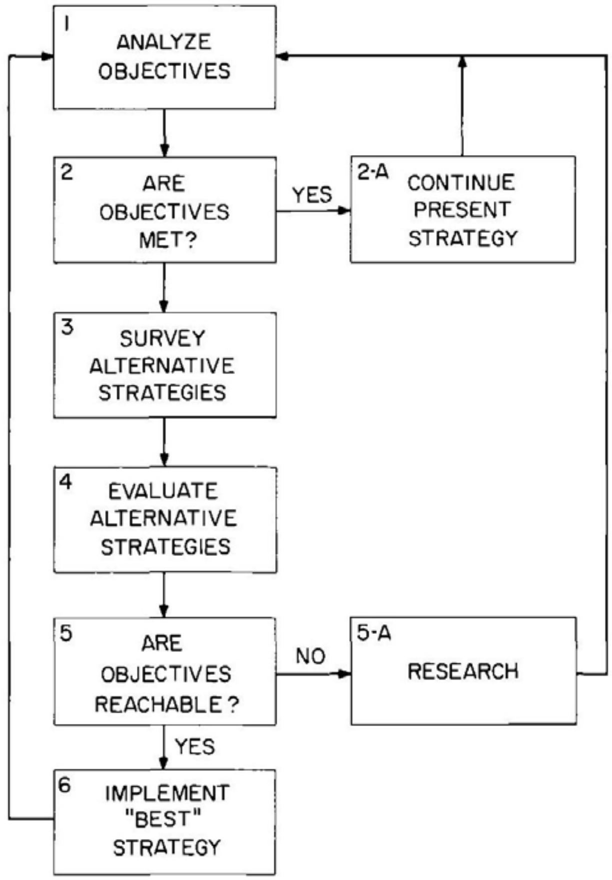

Figure 5. Example of an early decision analysis in fisheries management where unsatisfied management objectives trigger the development of alternate management strategies, which in turn are evaluated and ranked to determine the “best” strategy. Source: Powers et al. (1975).

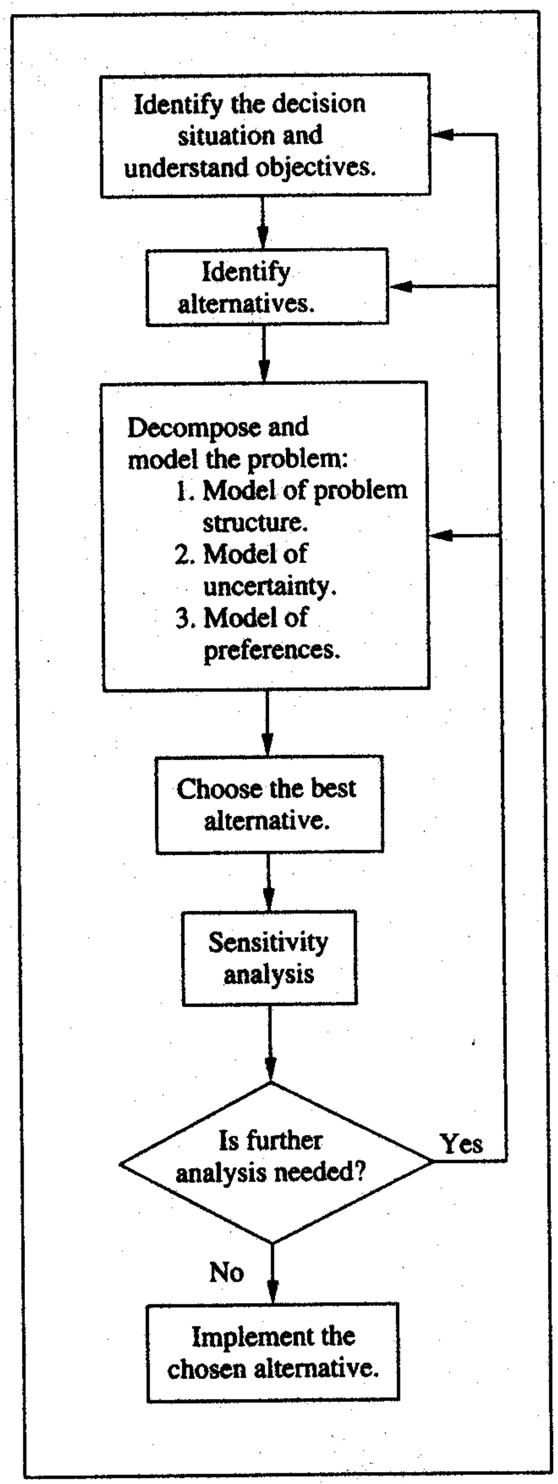

Figure 6. Process flowchart of Decision Analysis (DA) as presented by Clemens & Reilly (2001). Note the importance of management objectives, and uncertainty represented as alternatives (competing hypotheses).

A variety of other DA cycles have been presented in the fisheries literature, including 5-step cycles (McAllister & Kirkwood 1995, Punt & Hilborn 1997) and 6-step cycles (Robb & Peterman 1998, Haeseker et al. 2002). Most of these DA cycles are relatively similar in structure and function, with some variation in the degree to which a Bayesian approach is incorporated in the analysis. Walters and Hilborn (1976) suggested that Bayesian statistical analysis could be used to evaluate alternative fisheries policies. Punt & Hilborn (1997) recommended the combination of Bayesian approaches in stock assessment and decision analysis as a parsimonious way to facilitate working with a broader range of uncertainty, and to maximize historical experience gained in fisheries science when predicting consequence of management actions. While frequentist statistical approaches continue to dominate in resource management, it seems fitting that the work of Thomas Bayes should have such an enduring effect.

8-Step DA Cycle

For the purposes of this review, we have selected a current 8-step form of DA that has been developed and refined by Randall Peterman and his colleagues for application in resource management in general, and fisheries management in particular:

1. Management objectives;
2. Management options;
3. Uncertain states of nature;
4. Probabilities on the uncertain states of nature;
5. Model to calculate the outcome of each management action for each state of nature;
6. Decision tree or decision table;
7. Ranking of management actions;
8. Sensitivity analyses.

Each of these steps is described below in paraphrase from Peterman and Peters (1998) and Peterman & Anderson (1999).

Step 1: Management objectives

Management objectives are clear and unambiguous criteria for ranking management options. For instance, a management objective might be to minimize the expected human mortality rate due to some contaminant; another might be to maximize the expected economic value of annual harvests from a fish population.

Step 2: Management actions

Management options are alternatives from which the recommended management action will be chosen. Decision makers must think creatively about these alternatives so that the full range of possibilities is considered.

Step 3: Uncertain states of nature (hypotheses)

Hypotheses (uncertain states of nature) are the parts of an analysis that are explicitly considered uncertain. Hypotheses are logically possible explanations of cause and effect. They may include conceptually different models (qualitative hypotheses) or simply a range of different parameter values for some equation (quantitative hypotheses).

Step 4: Probabilities on uncertain states of nature (hypotheses)

Probabilities, or degrees of belief, can be placed on uncertain states of nature (hypotheses) in one of three ways. If sufficient long-term data are available, then these probabilities can be directly estimated. If data are limited, probabilities can be estimated on the basis of available evidence and/or expert opinions.

Step 5: Model to calculate outcomes of actions across states

Model predictions of consequences are generated for combinations of particular management options across possible states of nature. The model can be as simple as one or two equations or very complex. These consequences, or outcomes, are described in terms that relate directly to the management objectives (e.g. cultural values, dollar value of fish harvested, percent mortality rate, value of information, etc.).

Step 6: Decision trees/tables

Decision tables (e.g. Figure 7) present alternative management actions as columns, alternative hypotheses regarding states of nature with associated probabilities as rows, and expected values are represented as cells in the table. Decision trees (e.g. Figure 8) clearly illustrate their relationships and ranking of possible decisions. Alternative management options and uncertain states of nature are represented by branches emerging from nodes. The probability of each uncertain state of nature is shown explicitly for each option. Outcomes or consequences of each management option, given each state of nature, are shown at the ends of the tree branches. Figure 9 shows an example decision tree with calculated economic consequences that can be used to rank management actions in quantitative fiscal terms. Decision trees are recommended as a more effective presentation for multiple, nested uncertain states of nature, compared to decision tables.

Hypotheses	Probabilities	Potential Action 1	Potential Action 2
Hypothesis 1 H_1	P (H_1) = correct P_1	Consequence of Action 1, given P (H_1) = correct C_{11}	Consequence of Action 2, given P (H_1) = correct C_{21}
Hypothesis 2 H_2	P (H_2) = correct P_2	Consequence of Action 1, given P (H_2) = correct C_{22}	Consequence of Action 2, given P (H_2) = correct C_{22}
		Expected consequence of Action 1 = $(P_1 \times C_{11}) + (P_2 \times C_{22})$	Expected consequence of Action 2 = $(P_1 \times C_{21}) + (P_2 \times C_{22})$

Figure 7. Generalized decision table used in a decision analysis to calculate expected consequences of two potential management actions (#1 and #2), in the face of two different, possible states of nature and their probability of being true. Source: Peterman & Peters (1998).

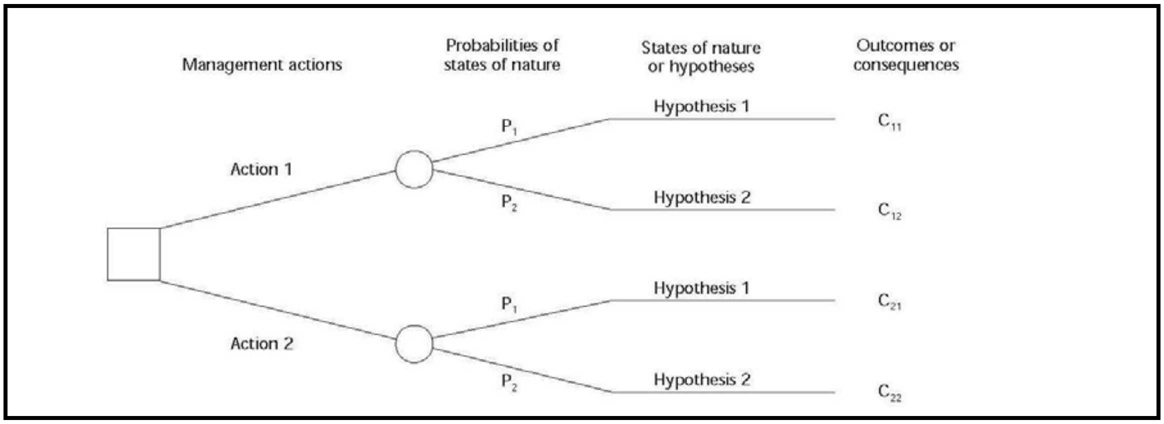

Figure 8. Generalized decision tree used in a decision analysis, to show the consequences of implementing two alternate management actions, under two different states of nature (hypotheses). Source: Peterman & Peters (1998).

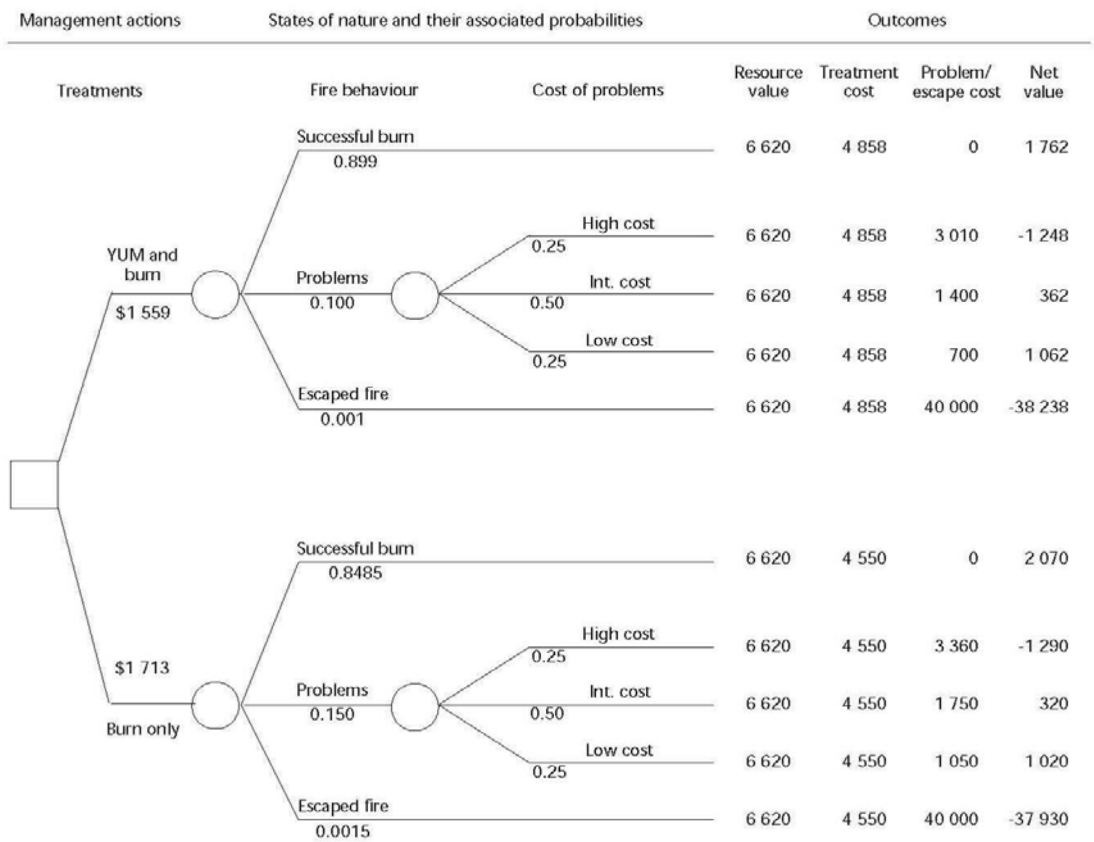

FIGURE 8.3 *Decision tree for the example described in the text for the Tahoe National Forest. The management options (treatments) are to "burn only" or "YUM and burn"; the latter refers to "yarding unmerchantable material," where the slash material from the logging operation is piled up before burning. Outcomes are costs in dollars for a 14-acre site. The resulting expected net resource values for each management option are indicated next to the option. See text for details. (Adapted from Cohan et al. 1984.)*

Figure 9. Example of a decision tree used in a decision analysis, to show the net economic consequences of implementing two alternate management actions, under three different states of nature (hypotheses) with varying probabilities and costs of consequences for alternate management actions. Source: Peterman & Peters (1998).

Step 7: Ranking of management actions

Management options are ranked by doing the calculations as indicated in the decision tree and comparing results according to the specified management objective(s). Each combination of state of nature and management option produces an outcome (e.g. net dollar value at the end of each branch), which is then weighted by its probability of occurrence. These weighted outcomes are summed for each management option in order to obtain its expected value (weighted average value). In this way, the effect of each hypothesis on the relative merit of a given management option is weighted by the relative degree of belief in that hypothesis.

Step 8: Sensitivity analysis

Sensitivity analysis indicates whether the rank order of management options changes under different assumptions. For instance, sensitivity analyses should be done for different management objectives, different sets of hypotheses (e.g. three possible structural forms of some relationship rather than two), or different probabilities on the range of parameter values. Sensitivity analyses will thereby identify the range of hypotheses, parameter values, or objectives over which the rank order of management options remains unchanged. Risk is evaluated through utility analysis of the decision-maker's tolerance of risk. Risk-seeking or risk-aversion may have a strong effect on value-based rankings.

3. DAAM

The third major section of this review focuses on something that should by now be clear to the reader – in a resource management context, DA and AM are more than complementary to each other, they need each other. To paraphrase Jones & Nudds (2003):

> "*Adaptive Management without Decision Analysis is inefficient, and Decision Analysis without Adaptive Management is unfinished business.*"

DAAM is all about making hard decisions in the face of uncertainty while reducing key uncertainties through management. By itself, AM can be a useful tool for managers to 'learn by doing,' however a primary focus on the scientific method can leave some managers and harvesters feeling that important day-to-day management issues are subservient to some higher calling to learn about the universe. DA helps to focus the efforts of AM in a very transparent and accountable manner. Similarly, DA by itself can be a useful tool for managers to organize their possible actions into a framework that explicitly incorporates their key uncertainties about the likely consequences of those actions. AM requires that if an uncertainty is important enough to be significant in a formal DA, then it is important enough to use management action as a tool to reduce that uncertainty – that's just common sense.

Origin and Development of DAAM

DAAM is not new. It was not created by Jones & Nudds (2003) when they helped the Saugeen Ojibway/Canada/Ontario Plenary draft the principles for implementation in their Fishing Agreement. The simple fact is that DA was present at the inception of AM, and it has been associated with AM throughout its development.

Consider the observation that "*Adaptive Environmental Assessment and Management*" (Holling 1978) was the third volume in the Wiley IIASA International Series on Applied Systems Analysis, which was managed in part by Howard Raiffa. In the Preface, Holling (1978) identified managing editors Raiffa and Levien as "*once more perform[ing] their unique roles as catalysts and supporters.*" To find direct evidence of DA in Holling (1978), one need go no further than Chapter 8 "Evaluation of Alternative Policies," the insightful summary of which we present below:

> "*Every single exercise in adaptive evaluation can and should begin with the development of a set of specific indicators responsive to the concerns of those who will make, and those who will endure, the policy decisions. These should be followed by an explicit graphical comparison of indicator patterns. As we have stressed repeatedly, if you must address the more subtle issues of evaluation, you will require expert assistance. Obviously, you should have no patience at all with consultants hawking "answers" in*

such an uncertain field. But even the most well-meaning and self-critical experts tend to be bound to their own specialties and techniques.

A recent report by a U.S. study group critically reviews past efforts to apply decision-theoretical approaches to specific environmental problems and provides an excellent perspective for would-be evaluators (Holcomb Research Institute, 1976). There are several good texts on applied decision theory in which you can read about these formal approaches to evaluation. We have found those by Raiffa (Raiffa, 1968; Keeney and Raiffa, 1976) to be the most readable. [...]

The notion that each policy should be associated with a probability distribution of outcomes reflecting uncertainties in the analysis is attractive and probably formally correct. Decision theory is well adapted to coping with such probability distributions. Unfortunately, people are not. Slovic and Lichtenstein (1971) summarize a body of evidence that suggests that a probabilistic assessment of utilities is most unlikely to lead to meaningful evaluations, even in the simplest cases.

In retrospect, it should be clear that the real problem of evaluation is not one of technique, but of meaning. The ultimate goal is not to produce a set of numerical rankings, but to understand the strengths and weaknesses of alternative policies' performances. For it is on the basis of such understanding that meaningful, adaptive steps can be taken toward policy modification, improvement, and eventual implementation." (Holling 1978, p.118)

Thus from the beginning of AM, decision theory in general, and DA in particular, played an important role in shaping the way that policies and hypotheses would interact in a science-based framework.

Similarly, one can find important references to DA in Walters (1986), especially in Chapter 6 "Embracing Uncertainty" where it becomes clear that DA and AM require each other to be effective and efficient:

"*It should be obvious that there is no really clear distinction between the preadaptive, adaptive, and certainty-equivalent phases of resource development. In particular, there is a large element of luck involved in whether early development decisions result in a solid basis for more thoughtful and experimental progress later. There is a large element of creativity (which also involves luck) in the imaginative discovery of untested opportunities and ways to pursue them with reasonable safety. And, finally, there is the danger that strong aversion to further change, or simple complacency, will result too early in the adoption of stabilizing policies that prevent further informative variation. In a sense,* ***it would be reasonable to say that the major role of formal decision analysis all along the way is to help maintain an open and balanced picture of what has been learned versus what remains open to question.***" (Walters 1986), p.164, our emphasis)

It is revealing to note that Walters (1986), p.184) explicitly stated that the ultimate goal of models is to be used in a DA.

Over the next 20 years, a variety of researchers implicitly or explicitly combined aspects of DA and AM in dealing with fisheries management issues (Walters 1977, Walters 1986, Walters & Green 1997, Link & Peterman 1998, Robb & Peterman 1998, MacGregor et al. 2002). McAllister & Peterman (1992b) found that over most of the conditions examined, experimentation yielded a higher present value of catches than status quo management of a pink salmon (*Oncorhynchus gorbuscha*) fishery in British Columbia, Canada. The authors argued that DA can satisfy the need of managers to be convinced that AM can be cost-effective, relative to non-experimental approaches, and that the tools can combine to effectively forecast potential economic yield of alternate management strategies. Peterman and Peters (1998) and MacGregor et al. (2002) described how DA can be used during the planning stage of an AM project to compare the expected performance of alternative experimental designs. McDaniels & Gregory (2004) identified advantages of treating learning as an objective within stakeholder processes with specific examples of successful stakeholder-based water flow management of hydroelectric power facilities (British Columbia, Canada), which included consideration of fisheries habitat and the diverse perspectives of agencies, First Nations and members of the public. Bundy (2004) explored the benefits of an active AM approach, within a decision-analytic framework, in San Miguel Bay, the Philippines. This analysis showed there to be no greater benefit to the resource from greater knowledge of the system, predicted by comparing 4 different population models, as compared with a single-hypothesis AM approach.

Value of learning (VOL*)*

The standard view of learning within DA is mostly limited to calculating 'the value of information' (VOI). But what happens if learning is itself established as one of the core management objectives? McDaniels & Gregroy (2004) introduced a powerful DAAM concept that they referred to as 'the value of learning' (VOL). Learning exists as the updating of probabilities of consequences of management alternatives – predictive information has value only if it has the potential to change the ranked order of management options. McDaniels & Gregory (2004) specifically identified this constraint in standard DA and proposed a broader perspective that recognizes additional benefits of incorporating learning in decision-making, including:

1. A better characterization of the management objectives;
2. New ways to more effectively implement existing management options;
3. Creating new management options; and
4. Improved understanding about the consequences/trade-offs of the various management options.

VOL can be very high if it has significant influence on important decisions.

In a DA context, VOL has been defined explicitly by McDaniels & Gregory (2004) in the following form (translated mathematically by us):

$$VOL = \sum_{i=1}^{i=n} [(U_{mo_{i,t}} | L_t) - U_{mo_{i,t-1}}]$$

where

VOL = value of learning
U = utility (a.k.a. expected value)
n = number of management options (*i,j, k, l, … n*)
$mo_{i,t}$ = *i*th management option
L_t = learning at time t

We view this concept of VOL as perhaps the simplest, and most elegant, description of how AM can be explicitly incorporated with DA in resource management decision-making.

DAAM for an Australian multispecies fishery

The work of Keith Sainsbury and colleagues (Sainsbury 1987, Sainsbury 1988, Sainsbury 1991, Sainsbury et al. 1993, Sainsbury et al. 1997) on an Australian multispecies fishery stands as one of the earliest and best examples of an integrated approach that included major facets of both AM and DA. The issue at hand was the expansion of a multi-species fishery off the NW continental shelf of Australia. Six structurally different population models were compared to investigate the decline of two economically valuable demersal species (*Lethrinus*, *Lutjanus*), relative to two less valuable demersal species (*Saurida*, *Nemipterus*). The decline was hypothesized to result from an unknown combination of intra- and inter-specific community interactions, and/or effects of gear on benthic habitat alteration. Forecasts of economic value of catch for alternate management strategies and a decision to expand fishery were evaluated, along with an examination of perceptions and consequences of the suggested 'learning period regimes.' The investigators developed 5 experimental AM regimes to evaluate each hypothesis and each regime weighted by probability of occurrence (from historical data) and Bayesian statistical inference. After six years of experimentation, managers observed that the chosen strategy generated data supporting the hypothesis of destructive trawling, and responsive appropriate changes to the organization of the fishery were implemented. The Sainsbury research team demonstrated how DA could be used to compare the potential economic performance of experimental and non-experimental strategies, and to refine experimental design for management of a large scale, multi-species fishery. Analysis of expected economic values of alternative experimental designs and of continuing with the existing regime helped managers come up with the most powerful and cost-effective design.

DAAM for watershed management planning

In 1999, Daniel Ohlson (1999) completed a M.Sc. Thesis at the University of British Columbia entitled “Exploring the Application of Adaptive Management and Decision Analysis to Integrated Watershed Management.” In this thesis, Ohlson explicitly focused on combining DA and AM for the development and application to land-use conflicts in Chapman and Gray Creeks, British Columbia, Canada – a system that was characterized by conflicting objectives and chronic uncertainty. Ohlson presented a process flowchart that specifically described how steps in the AM cycle intermesh with steps in the DA cycle (Figure 10). We view this independent evolution of integrated DAAM as a strong endorsement of the ideas that we are presenting in this review and proposal. Ohlson concluded that the major benefits of DAAM in his situation were (1) ability to reveal effect of key uncertainties on ranking of alternative management actions, and (2) increased confidence among stakeholders due to enhanced transparency and accountability. Ohlson did raise significant concerns about the resources (time, money, personnel, training and modelling capability) available for a complete treatment using all component parts of DAAM. However, he argued that the inclusive costs of not doing DAAM could significantly outweigh the costs of implementation.

DAAM for Columbia River salmon

Over the past decade, researchers associated with David Marmorek and ESSA Technologies Ltd. have been involved in the development and implementation of what may be the most advanced integration of DAAM to date (Deriso et al. 2001, Peters & Marmorek 2001, Peters et al. 2001, Marmorek & Peters 2002). The subject of this work is focused largely on recovery enhancement of depleted and endangered populations of Columbia River Basin chinook salmon (*Oncorhynchus tshawytscha*). Peters & Marmorek (2001) and Peters et al. (2001) used simulation models to evaluate three management actions for seven index stocks of Snake River spring and summer chinook salmon. The models compared different hypotheses about the true states of nature related to continuing current operation of the Columbia River hydropower system, maximizing transportation of smolts, and natural river drawdown (breaching) of four Snake River dams. By using DA and AM, the authors showed that robust recovery strategies could be identified before uncertainties were fully resolved, which may not occur until listed stocks have disappeared (Peters & Marmorek 2001). Simulated flow and monitoring allowed stakeholders and/or decision-makers the option to proceed with planned AM experimentation, given projected manipulation and power revenues. The authors warned that AM may only be warranted if any additional information resulted in the direct compliance with a particular objective as related to selection of a different management action.

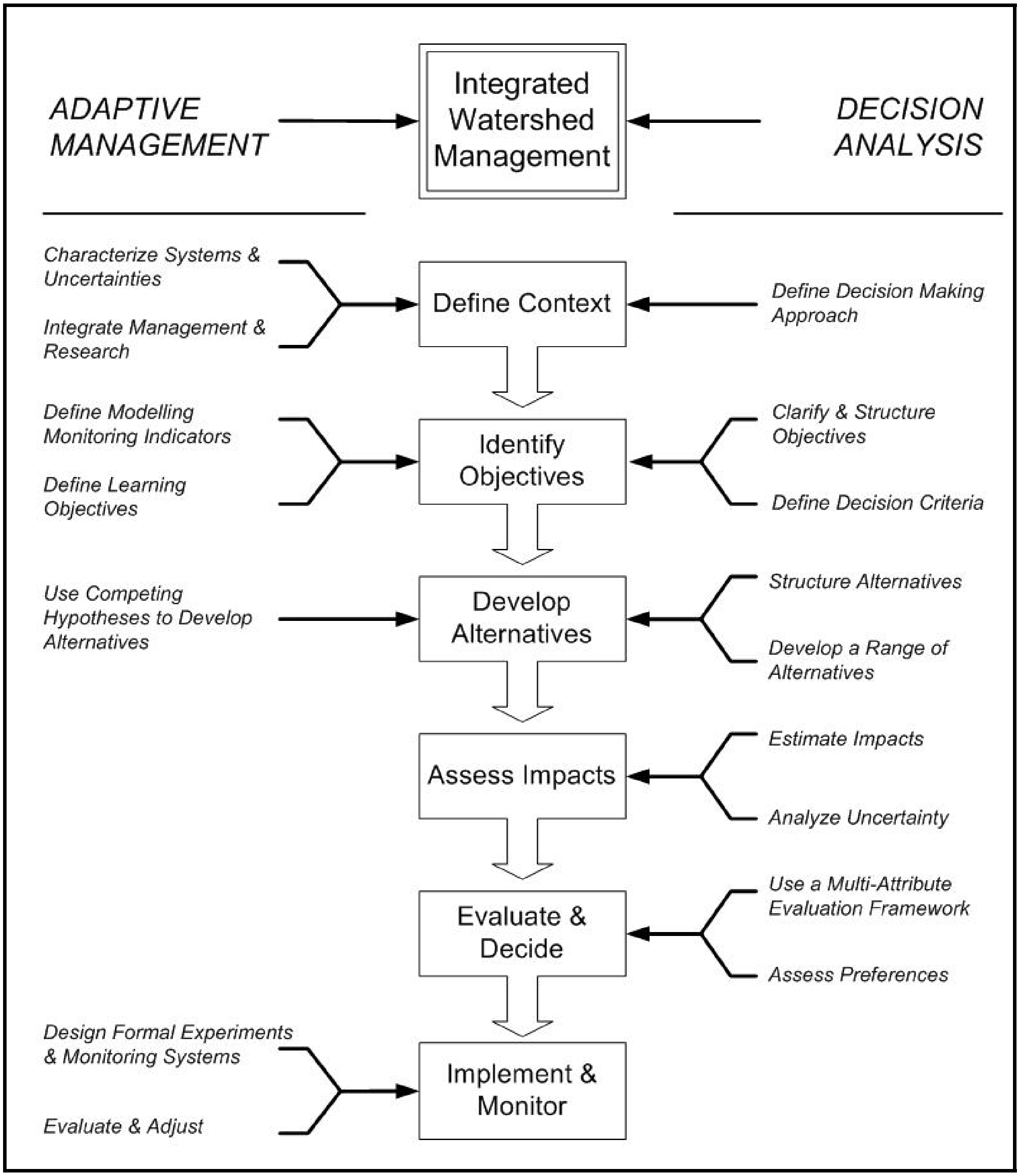

Figure 10. Flowchart representing the interaction between Adaptive Management and Decision Analysis (DAAM), as independently proposed for application to integrated watershed management by Ohlson (1999, p.31).

Essential principles of DAAM

On the basis the information reviewed in the DA and AM literature, we have identified a set of nine essential principles that characterize the integration of DAAM as a resource management tool (Figure 11). There are three essential principles associated specifically with the DA cycle of Peterman and Peters (1998) and Peterman & Anderson (Peterman & Anderson 1999).

- Expected value / utility
- Decision tree / table
- Sensitivity analysis

There are two essential principles associated specifically with the AM cycle of Murray & Marmorek (Murray & Marmorek 2003, Murray & Marmorek 2004a):

- Learning as a core management objective
- Update probabilities of hypotheses (learning)

Finally, there are four essential principles that are common to both DA and AM cycles mentioned above:

- Non-exclusive participation
- Explicit management objectives
- Probabilities of competing hypotheses
- Value of Information

We see this shared set of essential principles as a reflection of the fact that both DA and AM originate from a common lineage of thought about the role of uncertainty in resource management.

Practical template for DAAM applications

In order to reflect the operational integration of the essential DAAM principles, we have attempted to organize the actual steps and tasks that would be required to complete a DAAM cycle to deal with a given situation (Table 1). When designing this draft template, we tried to keep in mind a practitioner who could use a checklist to keep track of the things to do in a workplan. The 'steps' presented in the first column are intended to categorize tasks according to the focus of attention, while the 'tasks' are intended to represent important milestones that are dependent upon one another. Shading and numbers in the DA and AM columns are provided simply to show the relationship between this practical template and the DA and AM cycles from which they were derived.

As with any draft of this nature, we realize that there will be differences of opinion with other researchers and managers regarding structure and function, unnecessary tasks, important omissions, and some plain old-fashioned errors. We hope that the readers will take the time to share their perspectives with us, with the hope that we can refine this draft template in order to make it as efficient and effective as possible.

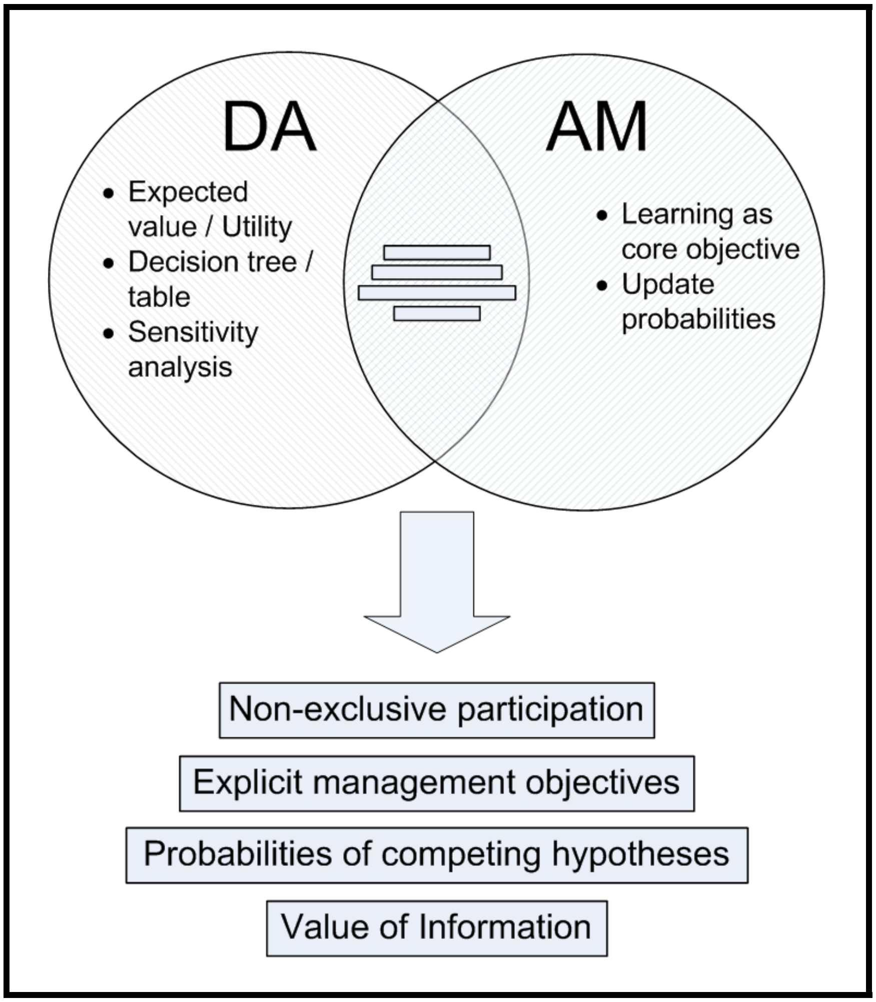

Figure 11. Essential principles associated with Decision Analysis (DA), Adaptive Management (AM), and those which are common to both combined as DAAM. This graphic shows the complimentarity and codependence of the two management techniques, which when integrated allow managers to make hard decisions in the face of uncertainty - while reducing key uncertainties by using management actions as a tool.

Table 1. A practical template for application of Decision Analysis/Adaptive Management (DAAM) to enable management decision-making in the presence of key uncertainties, while using management as a scientific tool to reduce key uncertainties. DA – refers to corresponding steps in the DA process as presented by (Peterman & Peters 1998, Peterman & Anderson 1999), while AM – refers to corresponding steps in the AM process as presented by Murray & Marmorek (2003, 2004a).

Step	Task	DA	AM
1. Define problem	Non-exclusive participation in process • identification of intersted parties: governments, users, NGOs, public • standing invitation to (1) receive reports, (2) participate in all aspects	**1**	**1**
	Identify core values related to the resource, including levels of risk aversion		
	Identify fundament objectives for management (clear, unambiguous, minimize X, maximize Y) that satisfy core values • learning objectives • social objectives • economic objectives • ecological objectives	**1**	**1**
	Compare objectives to identify consistency and conflict		
	Identify key indicators, performance criteria	**1**	**1**
	Identify key uncertainties (uncertain states of nature)	**3**	**1**
	Develop hypotheses for key uncertainties • qualitative (model parameters) • quantitative (parameter values)	**3**	**1**
	Assign (prior) probabilities to hypotheses • direct estimation (long term data) • Bayesian statistical estimation • expert opinion estimation	**4**	**1**
2. Design options	Identify means objectives that satisfy fundamental objectives		
	Identify alternative management options based on means objectives	**2**	**2**
	Predict (calculate) consequences of management options for each hypothesis	**5**	**2**
	Display predicted consequences of management options for each hypothesis • decision tree • decision table	**6**	
3. Rank order expected values	Weight each predicted consequence by probability of hypothesis	**7**	
	Calculate expected value (weighted average value) by summing weighted consequences for each management option	**7**	
	Highlight extreme predicted consequences (e.g. population crash)	**7**	
	Order rank of expected values from all combinations of hypotheses and management options	**7**	
	Identify management option with highest rank order of expected value of information	**7**	

4. Sensitivity analysis	Identify different sets of management objectives to be tested for sensitivity	**8**	
	Identify hypotheses for key uncertainties to be tested for sensitivity • qualitative (model parameters) • quantitative (parameter values)	**8**	
	Define conditions of management objectives and/or hypotheses to test for sensitivity • qualitative (presence/absence) • quantitative (range of values)	**8**	
	Determine if rank order of expected values for management options changes under different	**8**	
5. Select management option	Present ranked order of expected values with sensitivity analysis to decision makers	**8**	
	Decision makers select (a) management option or (b) competing hypotheses explaining another key uncertainty		**2**
6. Design management plan	Design implementation plan (treatment) to test: (a) predicted consequence of selected management option, or (b) predictions generated by competing hypotheses explaining another key uncertainty • specify competing hypotheses and predictions generated by those hypotheses • logistics, effort, documentation • contrasting treatments, replicates, randomization		**2**
	Conduct value of information (VOI) analysis to evaluate experimental management options		**2**
	Design monitoring plan • logistics, effort, documentation • accuracy, precision, power analysis		**2**
	Design data management plan • data standards, training, quality control		**2**
	Design data analyses • graphical, tabular, statistical		**2**
7. Implement management plan	Follow the implementation plan		**3**
	Provide interim reports of implementation results		**3**
	Be prepared for surprises in implementation		**3**
	Document and report implementation deviations		**3**
8. Monitor management plan	Follow the monitoring plan		**4**
	Provide interim reports of monitoring results		**4**
	Be prepared for surprises in monitoring		**4**
	Document and report monitoring deviations		**4**
	Report if plan objective was achieved		**4**
9. Evaluate results	Design implementation plan (treatment) to test: (a) predicted consequence of selected management option, or (b) predictions generated by hypotheses to explain another key uncertainty		**5**
	Compare predicted versus observed results		**5**
	Report statistical significance of differences		**5**
	Assign updated (posterior) probabilities to hypotheses • direct estimation (long term data) • Bayesian statistical estimation • expert opinion estimation		**5**
	Conduct value of learning (VOL) analysis to evaluate the importance of new information		

	Report how the key uncertainty has been reduced (what has been learned)		**6**
10. Refine the problem	Re-State fundamental objectives for management (previous and new, clear, unambiguous, minimize X, maximize Y) • learning • social • economic • ecological		**6**
	Re-Identify key indicators, performance indicators (previous and new)		**6**
	Re-Identify key uncertainties (uncertain states of nature, previous and new)		**6**
	Re-Develop hypotheses for key uncertainties (previous and new) • qualitative (model parameters) • quantitative (parameter values)		**6**
	Re-Assign probabilities to hypotheses (previous and new) • direct estimation (long term data) • Bayesian statistical estimation • expert opinion estimation		**6**
Iterate	Return to 'Design options' above		**6**

DA steps: (1) management objectives, (2) management options, (3) uncertain states of nature, (4) probabilities on the uncertain states of nature, (5) model to calculate consequences, (6) decision tree or decision table, (7) ranking of management actions, and (8) sensitivity analyses (Peterman & Peters 1998, Peterman & Anderson 1999).

AM steps: (1) define the problem, (2) design actions to test hypotheses, (3) implement actions, (4) monitor implementation, (5) evaluate results, (6) revise uncertainties (Murray & Marmorek 2003, 2004a).

DAAM for Great Lakes fisheries management

There is already a good track record for application of DA and AM in the management of Great Lakes fisheries.

As early as the late 1970's the Ontario Ministry of Natural Resources highlighted the possibility of using AM to deal with key uncertainties in Lake Erie fisheries management planning (Kendall et al. 1977).

Walters (1986) used the example of lake trout rehabilitation in the Great Lakes as a case study to demonstrate some of the problems that can be encountered in designing adaptive policy for complex problems (Chapter 11). Walters discussed the fundamental conflict between rehabilitation and put-and-take stocking programs, and raised the idea of "surfing on the cliff edge" between population yield and harvest rates (Walters et al. 1980).

In the early 1980s, the Board of Technical Experts of the GLFC approved a plan to apply the techniques of Adaptive Management to some of the complex problems in Great Lakes fisheries management, specifically a problem in the interactions of salmonids (native and exotic) and sea lamprey (exotic). In 1981 the GLFC sponsored an extensive trial of AM, led principally by Carl Walters and Buzz Holling (Koonce et al. 1982, Minns et al. 1984), including workshops that focussed specifically on:

1. trade-offs among lamprey control, lake trout stocking and fishery regulation given the objective of lake trout rehabilitation, with an emphasis on Lake Michigan (Milliman et al. 1987a);
2. integrated pest management and sea lamprey control on Lake Superior (Jacobsen et al. 1985);
3. consequences for the fish community and fisheries of various quota management policies for walleye, yellow perch and white bass on Lake Erie.

The models emerging from these workshops became the basis of generalized decision support tools developed to evaluate the long-term patterns of sea lamprey production and the impacts on fish populations (Christie & Goddard 2003). Milliman et al. (1987a, 1987b) proposed AM as a means to evaluate the success of rehabilitation of the lake trout fishery in the Great Lakes and to make policy choices. The GLFC response presented by Minns et al. (1984) indicated that there was a "strong mandate for further use of the [AM] process by the Commission and its collaborating agencies."

Over the next twenty years, a variety of projects proposed or applied the concepts of DAAM to assist in (1) making hard fisheries management decisions in the face of uncertainties, and (2) reducing those uncertainties through management. Johnson et al. (1992) used an adaptive management framework to evaluate the effect of a rehabilitation plan on the yellow perch fishery in Lake Michigan. Hartig et al. (1996) investigated the relationship between habitat rehabilitation and aquatic resource management objectives in the Great Lakes, and explicitly recommended that habitat rehabilitation programs should be implemented in an AM context. Jones et al. (Jones et al. 1996) recommended the adoption of AM to reduce key uncertainties in the relationship between threats to fish habitat and the effects on productive capacity of Great Lakes aquatic ecosystems. Schneider & Lockwood (Schneider & Lockwood 1997) reported on a 1985 workshop conducted by the Michigan DNR recommended that an adaptive management approach be taken to fishery management in Michigan (presumably including Great Lakes fisheries).

In 1998, the Ontario Ministry of Natural Resources hosted a special "Adaptive Management Forum" (MacDonald et al. 1999) which, among other topics, examined the role of AM in dealing with Great Lakes fisheries issues. Priority issues for AM-oriented programs in Great Lakes fisheries management included:

1. Cage culture: Cage culture risk includes eutrophication, escapes, and conflicts with other natural resource user groups. OMNR should implement an adaptive study to evaluate the siting of cage culture operations, pollution control, and operational practices. The study should be continued long enough to provide contrasts among years.
2. Salmonid stocking: OMNR has an ongoing experimental management program to reintroduce Atlantic salmon to Lake Ontario. While stocking is socially desirable, its scientific impacts are unclear and require examination. AM of stocking should start with simple systems having the best potential for success. The goals must be communicated to all stakeholders from the outset.
3. Quota setting: Conflict resolution tools are required for commercial fish quota disputes. AM could provide a tool with which to involve commercial fishers in an explicitly rationalized, scientifically based, and transparent decision-oriented program. (MacDonald et al. 1999)

Jones & Haeseker (2001) used a 6-step DA cycle to develop a decision model for the St. Marys River sea lamprey control program, where the key uncertainties were identified as:

- sea lamprey larval distribution and its effect on Bayluscide treatment effectiveness;
- larval demographics (i.e., uncertainties in growth, survival and transformation rates of larvae); and
- adult to age 1 stock-recruitment relationship.

Using DA, Haeseker et al. (2003) were able to evaluate the effects of compensation and stock-recruitment uncertainty on management options available for St. Marys River sea lamprey control. In this article, the authors made specific reference to a GLFC "*recognition of the importance of uncertainty*" and a request that uncertainty "*be incorporated into the decision-making process whenever possible.*"

Lester et al. (2003) indicated that while AM has not yet been applied to recreational fisheries in Ontario, they strongly recommended AM for choosing among alternative management actions for recreational fisheries in Ontario's inland lakes:

> "*Management agencies and stakeholders speak about sustainable use, yet action is typically focused on a short window into the future. Recent changes in Ontario's fishing regulations will probably see us through another decade before increases in fishing effort exceed the level that these regulations are designed to handle. It will be a much bigger step to think in terms of the next century when seeking a solution. We expect that when this step is taken stakeholders will accept an active adaptive management approach and the province will embark on a new path of learning. Until then, Ontario's management efforts will be focused primarily on monitoring the increased demand for fishing and devising counter measures to lessen its impact.*" (Lester et al. 2003, p.1326)

While Lester et al. (2003) did not specifically mention AM for Great Lakes fisheries (recreational or commercial), many of the challenges are very similar to those associated with inland lake fisheries.

In "Wisconsin's Comprehensive Management Plan To Prevent Further Introductions and Control Existing Populations of Aquatic Invasive Species," The Wisconsin Department of Natural Resources stated that it was implementing an AM program (WDNR et al. 2003). AM has also been strongly advocated in Michigan DNR rehabilitation plans for walleye in Saginaw Bay, Lake Huron (Fielder 2002, Fielder & Baker 2004).

The Lake Erie Walleye Task Group worked with Mike Jones and colleagues to develop a DA support tool to improve the ability of the GLFC Lake Erie Committee to incorporate uncertainty and risk into management:

> "*The DA model describes the long term outcome of a simulated fishing management policy, quantifies uncertainties specific to the Lake Erie walleye population, and provides managers with critical information about the variability of the walleye population. The current version of the DA model is applicable to the Lake Erie walleye population until additional information is provided that might change what is currently known about this population (e.g., additional information on natural mortality, stock structure or recruitment). At this time, the charge to the WTG to assist with the development of the DA model has been completed. In the future, with the availability of new information, the WTG may be tasked to update and execute the DA model again.*" (LEWTG 2005)

It is clear from this description that the Lake Erie DA model would derive significant benefit by viewing DA as the ongoing, iterative cycle that it is (and by considering the management advantages of dealing with that "new information" in a structured AM manner).

Based on this brief historical tour through Great Lakes fisheries issues, it should be very clear that there is ample need for a practical, integrated tool that combines the strengths of both DA and AM.

4. Conclusions

First and foremost, we would like to extend our sincere thanks to the readers who took valuable time to review this draft discussion paper. As we indicated above, we would greatly appreciate any and all feedback on our work. We encourage you to contact us at your earliest convenience so that we can benefit from your knowledge, experience and ideas related to DAAM.

Second, we want to highlight a few key points that we hopefully raised (implicitly or explicitly) in this draft:

- Why bother? Because we need fisheries management that is transparent and accountable, and DA + AM are the best tools that we can think of to get the job done.

- Process, not product. The process of DA is a cycle. The process of AM is a cycle. The process of Science is a cycle. If we want ‘science-based management’ we will necessarily have to plan on doing management in explicit feedback cycles.

- There is inherent value in performing steps of DAAM. There is a lot of thinking behind those steps. Each one is there for a reason; managers and researchers should be required to know what each of those reasons is.

- Transparency & accountability. If you implement DAAM, you will ensure a high degree of both. Some might argue that you could achieve full transparency and accountability with DA alone, however the management decision-makers would still be accountable for the fact that they did not actively attempt to reduce a key uncertainty through management when they had the chance.

- DAAM means never having to say you’re sorry. We are here to make managers look good. They will not have to stand up in front of angry crowds and suffer the slings and arrows hurled by people who feel misled or marginalized. Ironically, the greatest benefit of DAAM is being able to confidently state “I do not know why this is happening” ... “but I have a way of making hard decisions in the face of that uncertainty, and a way of using the existing management program to find out why it is happening.”

SC, SM & KR

5. Acknowledgements

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Appendix I. Draft principles of Decision Analysis and Adaptive Management, prepared for the Saugeen Ojibway/Canada/Ontario Plenary. Mike Jones & Tom Nudds, 14 February 2003.

1. Uncertainty is pervasive and has a big effect on ability to make wise decisions.[1]

2. DAAM must be clearly understood.[2]

3. DAAM requires a careful, inclusive specification of the management system.[3]

4. To be effective, DAAM depends on meaningful involvement of all stakeholders.[3]

5. Decision analysis and adaptive management depend on one another to be effective.[4]

6. Successful, inclusive DAAM requires these steps:

    a. All parties involved.
    b. Inclusive specification of management objectives and options.
    c. Identification of critical uncertainties, as hypotheses.
    d. Critical, rigorous examination of evidence for alternative hypotheses.
    e. Development of models to forecast outcomes of management, given different hypotheses.
    f. Evaluation and ranking of competing hypotheses by likelihood in light of uncertainty (simple DA).
    g. Evaluation of experimental management options (DA - value of information analysis).
    h. Design and implementation of management experiments according to sound principles of experimental design.
    i. Monitor key responses.
    j. Update ranking of competing hypotheses by likelihood given monitoring results.

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[1]No management decision is without risk. To be sure, learning about risk occurs as part-and-parcel of DA insofar as DA facilitates risk “assessment”, but risk is not necessarily reduced as a result. Uncertainty, and hence risk, remain until tests are performed that explicitly address the key uncertainties that present risk, that is, until risk is actually assessed as a result of applying experimental management.

[2]A clear understanding of DA and AM is essential: combined, they amount to “learning while doing”, not “learning, then doing”. The latter is referred to now as “muddling through”, and is not the preferred option in modern natural resources management. Management agencies often refer to “flexible” management as adaptive management and to “systematic, objective” decision-making as decision analysis. This is wrong. Both are incorrect uses of the terms because they fail to explicitly acknowledge uncertainty and the opportunity to learn.

[3]Unless the management system is fully specified and inclusive, key uncertainties will remain outside the ability of managers to address through DAAM, thus further contributing to risk. The most advanced, large-scale example of AM currently in place (mallard harvest management) has learned from experience that the proper identification of populations and, by extension, stocks within populations, is a key requisite to successful application of DA and AM. This is generally true of any widespread, renewing, biological populations that represent common property resources. Caribou management boards, for example, successfully brought together all of the users throughout the range of particular migratory herds with a view addressing key differences of opinion among the users with respect to the factors that affected the shared resource.

[4]DA and AM are more than simply complementary. Complementarity implies merely existing side-by-side, but not necessarily co-dependent. Experimental management without DA is inefficient, and DA without experimental management is unfinished business.

Appendix II. 'Ten commandments' for good policy analysis (Morgan & Henrion 1990, p.37), used in the development and proposal of DAAM for fisheries management.

1. **Do your homework with literature, experts, and users.**
2. **Let the problem drive the analysis.**
3. **Make the analysis as simple as possible, but no simpler.**
4. **Identify all significant assumptions.**
5. **Be explicit about decision criteria and policy strategies.**
6. **Be explicit about uncertainties.**
7. **Perform systematic sensitivity and uncertainty analysis.**
8. **Iteratively refine the problem statement and the analysis.**
9. **Document clearly and completely.**
10. **Expose the work to peer review.**