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# EMDS 3.0: A modeling framework for coping with complexity in environmental assessment and planning

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**Abstract** The Ecosystem Management Decision Support (EMDS) system is an application framework for knowledge-based decision support of ecological assessments at any geographic scale. The system integrates state-of-the-art geographic information system (GIS) as well as knowledge-based reasoning and decision modeling technologies to provide decision support for a substantial portion of the adaptive management process of ecosystem management. EMDS 3.0 is implemented as an ArcMap® extension and integrates the logic engine of NetWeaver® to perform landscape evaluations, and the decision modeling engine of Criterium DecisionPlus® for evaluating management priorities. Key features of the system's evaluation component include abilities to (1) reason about large, abstract, multi-faceted ecosystem management problems, (2) perform useful evaluations with incomplete information, (3) evaluate the influence of missing information, and (4) determine priorities for missing information. A key feature of the planning component is the ability to determine priorities for management activities, taking into account not only ecosystem condition, but also criteria that account for the feasibility and efficacy of potential management actions. Both components include powerful and intuitive diagnostic features that facilitate communicating the explanation of modeling results to a broad audience.

**Keywords: natural resources, modeling, assessment, analysis, planning, software, ecosystem management.**

The Ecosystem Management Decision Support (EMDS) system is an application framework for knowledge-based decision support of ecological assessments at any geographic scale. The system integrates state-of-the-art geographic information system (GIS) as well as knowledge-based reasoning and decision modeling technologies in the Microsoft Windows® (hereafter, Windows) environment to provide decision support for a substantial portion of the adaptive management process of ecosystem management.

EMDS version 3.0 was developed for the USDA Forest Service under contract with the Environmental Systems Research Institute (ESRI, Redlands, CA) to provide decision support for landscape analysis and planning. The initial release of version 1.0 in February 1997 integrated logic processing of landscape information, based on the NetWeaver® fuzzy logic engine (Rules of Thumb, Inc.), into the ArcView GIS environment[1]. EMDS version 3.0 is a major re-engineering of the system for ArcGIS 8.1 (or later) COM-based technology and Windows XP or 2000[2]. Version 3.0 extends the original scope of the EMDS application to include integrated planning functions provided by the Weighted Decision Object, an engine by InfoHarvest (Seattle, WA) that implements the analytic hierarchy process model[3,4] (AHP) for setting priorities, selecting alternatives, and allocation of organizational resources.

The assessment and planning features of EMDS version 3.0 are illustrated with an integrated, multi-scale example designed to (1) evaluate salmon habitat potential in stream reaches and subwatersheds, and (2) establish priorities for protection and restoration of stream reaches and watersheds, based on results of landscape assessments and additional considerations of restoration efficacy and feasibility.

## 1 Background

Beyond GIS, the core technologies underlying EMDS are likely to be unfamiliar to many, if not most readers, so this section provides a general overview of concepts related to logic and decision modeling.

### *1.1 Logic-based modeling*

Basic concepts of approximate reasoning with fuzzy logic were first presented by Zadeh[5,6]. Subsequent concept papers[7–9] elaborated on the syntax and semantics of linguistic variables, laying the foundation for what has become a significant branch of applied mathematics. Fuzzy logic is concerned with quantification of set membership and associated set operations. Formally[10], let $E$ be a set, denumerable or not, and let $x$ be an element of $E$. Then a fuzzy subset $A$ of $E$ is a set of ordered pairs $\{x, A(x)\}$, in which $A(x)$ is a membership function that takes its values from the set $M = [0, 1]$, and specifies the degree of membership of $x$ in $A$. Because fuzzy set theory is a generalization of Boolean set theory, most Boolean set operations have equivalent operations in fuzzy subsets[10].

Application of fuzzy logic to natural resource management is still relatively novel. General areas of application include classification in remote sensing[11], environmental risk assessment[12], phytosociology[13,14], geography[15], ecosystem research[16], and environmental assessment[17, 18]. More specific applications include catchment modeling[19], cloud classification[20], evaluation of plant nutrient supply[21], soil interpretation[22,23], land suitability for crop production[24], ecological site classification[25], watershed assessment for total maximum daily load of non-point source pollutants[26], and biodiversity system design[27].

A logic model represents knowledge about how to solve a problem in some domain of interest. Several different approaches to knowledge-based representation have been developed over the last 30 years[28]. EMDS incorporates the NetWeaver logic engine for knowledge-based reasoning[29,30]. This system implements a logic model as hierarchies of dependency networks. The logic model that an assessment team constructs with NetWeaver is best thought of as a meta database that interprets data processed by an inference engine.

An aspect of logic-based modeling that makes it quite useful in ecological assessment is that such systems can reason with incomplete information. For example, the NetWeaver engine provides partial evaluations of ecosystem states and processes, based on available information; it also provides useful information about the influence of missing data which can be used to improve completeness of an assessment. In the future, assessment teams may be able to assemble a list of all topics they want to include in an assessment, assemble a list of data requirements needed to address those topics, and find they have all the required data. For the foreseeable future, however, assessments routinely need to deal with incomplete data. There may be some missing observations for several to many data types. There may be no data at all for possibly many others. The NetWeaver engine incorporated into EMDS uses a simple algorithm to compute the influence of missing data based on the logical structure of the model, how many states and processes use the information, and at what level the information enters the model structure. The Data Acquisition Manager (DAM) in EMDS uses information about data influence to assist users with prioritizing new data acquisition needs.

### *1.2 Decision modeling*

A multi-criteria decision problem generally involves choosing one of a number of alternatives based on how well those alternatives rate against a chosen set of structured and weighted criteria (the decision model). The criteria themselves are weighted in terms of importance to the decision maker, and the overall score of an alternative is the weighted sum of its rating against each criteria. The ordering of the alternatives by their decision scores is a prioritized ranking of those alternatives by preference. Decision analysis provides a number of analytic tools, such as sensitivity analysis and tradeoff analysis that validate the reasonableness and robustness of a given decision model. Two primary decision-making methodologies in wide use are the Analytical Hierarchy Process (AHP; 3) and Multi-attribute Utility Theory as implemented in the Simple Multiattribute Rating Technique[31,32] (SMART).

## 2 EMDS system components

The EMDS component diagram illustrates the basic architecture of EMDS 3.0 and the flow of information among system components (Fig. 1). Note that NetWeaver Developer and Criterium DecisionPlus® are external development tools needed to create logic and decision models, respectively. Major components of EMDS are described in the following subsections.

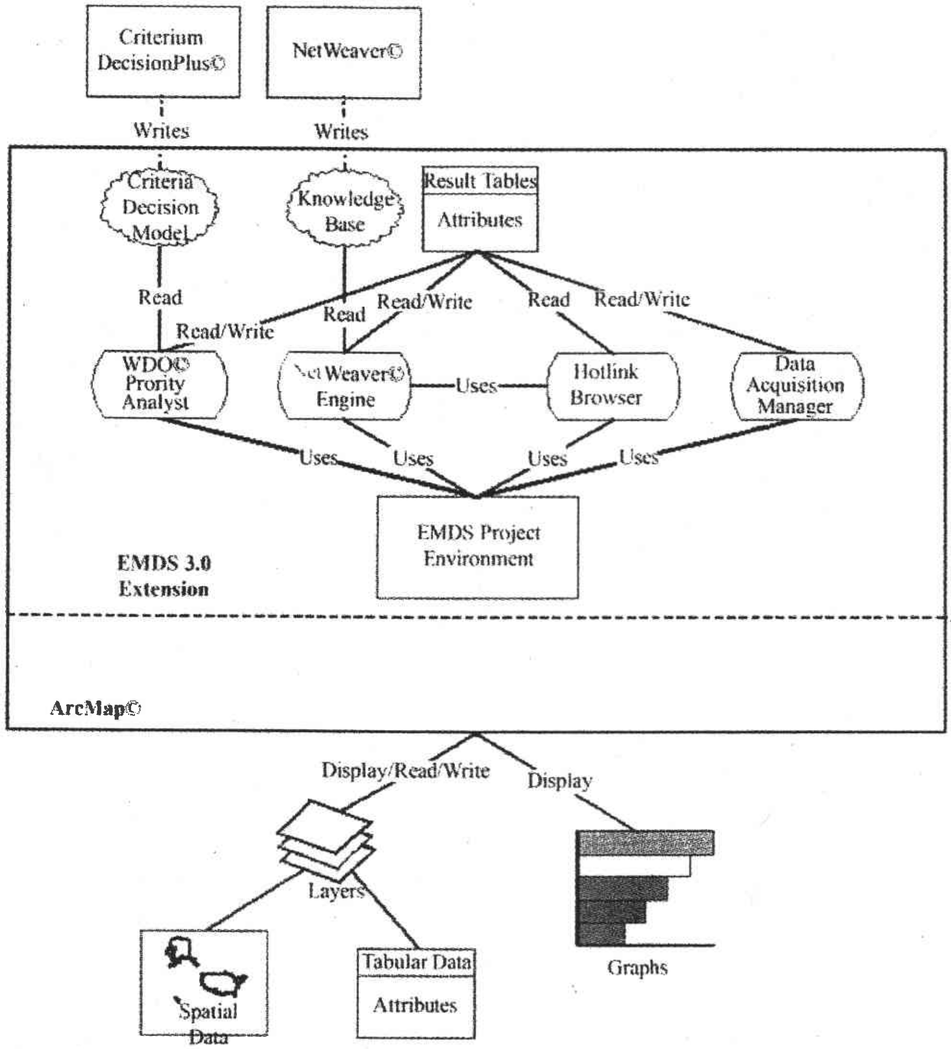


Fig. 1. EMDS component diagram. Strength of evidence for topics in logic models is determined by the NetWeaver engine. The Priority Analyst uses output from the NetWeaver engine to develop management priorities for landscape features, based on decision models developed with Criterium DecisionPlus. The Hotlink Browser provides an intuitive graphic interface to trace the derivation of conclusions generated by the logic engine (Fig. 3). The Data Acquisition Manager develops priorities for missing data, based on summary information about the influence of missing data and additional logistical considerations provided by a user.

## *2.1 ArcMap*

ArcMap is the spatial processor that executes spatial overlays, table joins, and provides other sophisticated GIS functionality. Rendered as an ArcMap extension, EMDS takes advantage of ArcMap's data management operations to perform all the processing required to prepare NetWeaver input tables. Results of an EMDS assessment are displayed in ArcMap's data view (Fig. 2), graphs, and tables.

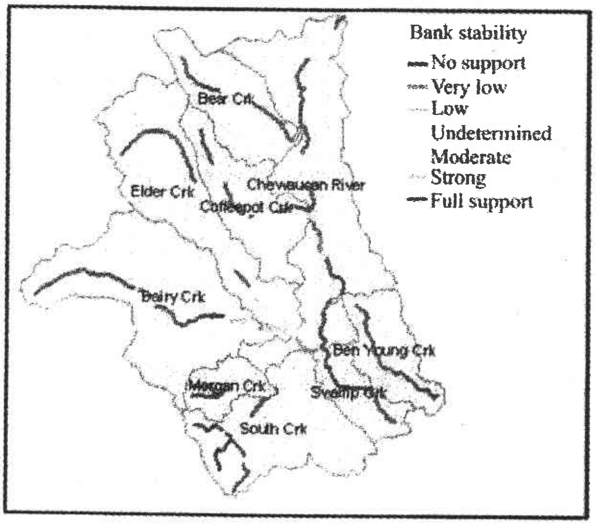


Fig. 2. Maps are the basic product of an EMDS analysis. This example illustrates one of 15 maps, relating to the evaluation of stream reaches in the Chewaucan Basin that could have been displayed in the ArcMap data view. Maps displaying the evaluation of NetWeaver topics are symbolized to indicate the strength of evidence for the associated proposition.

### 2.2 *EMDS project environment*

The EMDS ArcMap extension provides the primary system interface in which users construct a project. A single EMDS project may contain multiple scales of landscape assessment, an assessment may contain multiple analyses, and analyses may contain multiple scenarios. To facilitate creation and management of projects, version 3.0 adds an EMDS pane to the ArcMap table of contents, and this pane represents the complete project structure in a collapsible outline view.

### 2.3 *NetWeaver logic engine*

Knowledge-based processing in EMDS is performed by the NetWeaver engine (Fig. 1). Data input to the engine is mediated by the EMDS Project Environment and ArcMap. Knowledge bases that describe logical relations among ecosystem states and processes of interest in an assessment are created in NetWeaver Developer (Rules of Thumb, Inc.). The NetWeaver logic engine evaluates data against a knowledge base that provides a formal specification for the interpretation of data. The logic engine allows partial evaluations of ecosystem states and processes based on available information, making it ideal for use in landscape evaluation where data are often incomplete. The NetWeaver engine was selected as the core logic processor of EMDS because its associated development system readily supports design of logic specifications for the types of large, complex, and abstract problems typically posed by ecosystem management.

A second key feature provided by the logic engine is the ability to evaluate the influence of missing information on the logical completeness of an assessment. The engine, in conjunction with the EMDS Project Environment and the Data Acquisition Manager, provides diagnostic tools for determining which missing data are most valuable given currently available data and for determining how much priority to give to missing data given other logistical information.

### 2.4 Hotlink Browser

After map output for an analysis has been displayed in ArcMap, the Hotlink Browser can be used to view the evaluated state of NetWeaver logic models for selected map features. The graphic display of the evaluated state of a knowledge base is relatively intuitive, and provides a detailed explanation of the derivation of evaluations that is extremely valuable to EMDS developers, users, and the general public (Fig. 3).

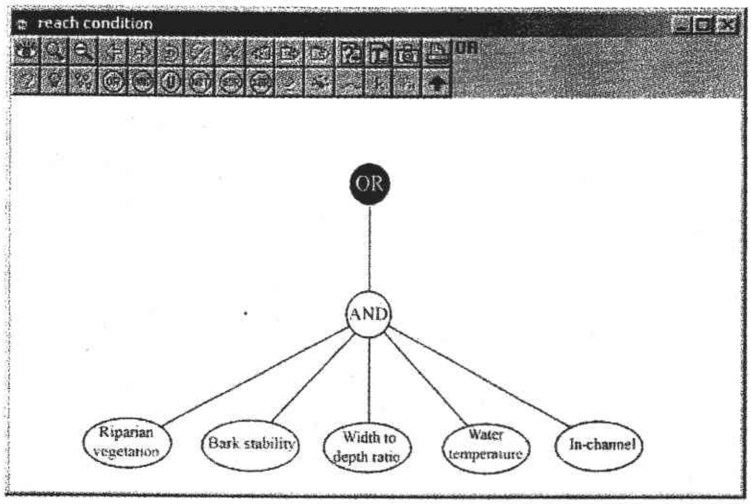


Fig. 3. Logic diagram for the evaluated state of the reach-condition topic in the assessment of stream reaches. The diagram displays the state of reach condition for a specific map feature that had been selected with the Hotlink Browser (Fig. 1).

Sophisticated geographic analyses often produce impressive looking maps. However, if the analytical system that produces a map cannot also explain the derivation of analysis results being portrayed in a relatively simple and straightforward way, then the system appears to observers as a black box. With the high level of public interest in natural resource management in these times, black box solutions are a political liability. Using the Hotlink Browser, users can navigate the networks of analysis topics to trace the logic of evaluations in an intuitive interface (Fig. 3). More importantly, the presentation of results in this graphic format is sufficiently intuitive that users of the system can use the Hotlink Browser as an effective communication tool that effectively explains the basis of evaluation results to broad audiences.

### 2.5 Data Acquisition Manager (DAM)

Data gaps are common, particularly in the early stages of landscape evaluation. It turns out that, from a logic perspective, the influence of missing information is very dynamic. The Data Acquisition Manager (DAM), in conjunction with the NetWeaver logic engine and the EMDS Project Environment, summarizes the influence of that missing information, given the information that is currently available, and assists the user with establishing priorities for obtaining the missing data to improve the logical completeness of an assessment in the most efficient way. A variety of maps, tables, and graphs provide useful information about what data are missing, the influence of missing data on completeness of the assessment, and how it is distributed in the landscape.

### 2.6 *Priority Analyst (PA)*

The PA is a dynamic decision tool that extends the functionality of EMDS to include integrated planning, based on decision models designed with Criterium DecisionPlus (Fig. 4, InfoHarvest). The PA is used for priority setting, resource allocation, and trade-off analysis once a landscape analysis has been completed. Just as the Hotlink Browser provides useful explanation facilities for understanding evaluation results, PA includes a variety of diagnostic tools that help developers, users, and the general public understand the basis for resultant planning priorities.

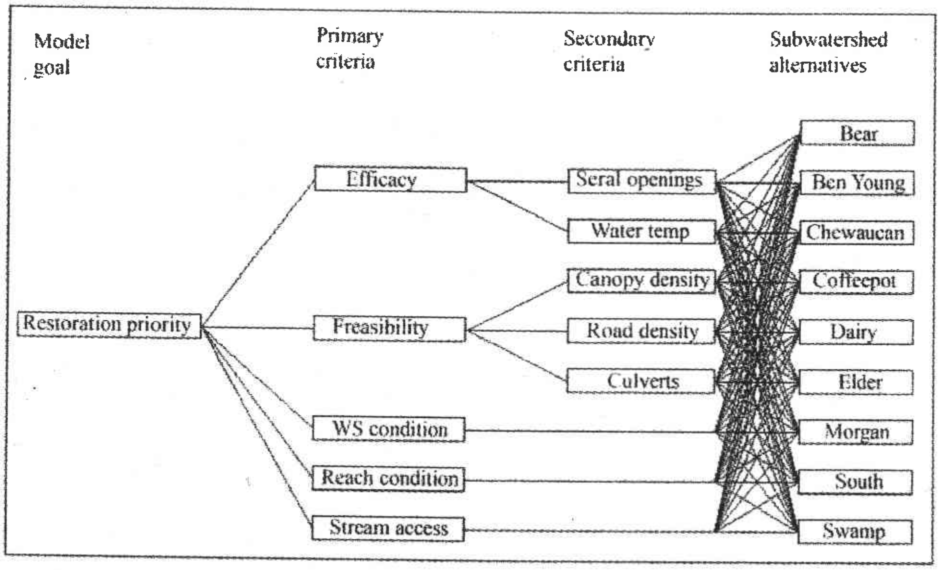


Fig. 4. A decision model, designed with Criterium DecisionPlus, for establishing priorities for watershed protection and restoration. The model is processed by the Priority Analyst compoment (Fig. 1).

Whereas the logic engine addresses questions about the current state of the assessment area, PA addresses questions about where to direct management for best effect. For most applications of evaluation and planning, maintaining this distinction is important because the landscape elements in the poorest condition are not necessarily also the best candidates for management activities such as restoration for example.

PA is a Multi-Criteria Decision Analysis (MCDA) component that assists resource managers in ranking landscape elements based on how well each rates against a set of decision criteria. Using output from a landscape evaluation and a decision model designed in Criterium DecisionPlus, PA rates the landscape elements not only with respect to their condition, but also with respect to factors related to the feasibility and efficacy of management. PA implements two decision models: AHP[3, 4] and SMART[33].

## 3 EMDS projects

### 3.1 Project structure

Each assessment is defined by its study area and a set of associated layers. In the Chewaucan example, there is a reach- and a subwatershed-level assessment. Assessments may contain one or more analyses. An analysis is defined by the logic model with which it is associated. Separate analyses within an assessment may be desirable to evaluate different logic models that use different combinations of an assessment's associated layers.

Input data and model structure cannot be edited in an analysis. This read-only feature of analyses is enforced to assure model and data integrity. However, users can create one or more scenarios in which both data and some aspects of knowledge-base structure can be modified either to tune the analysis or explore alternative conditions and hypotheses about the state of the landscape.

### 3.2 Multiple scales of assessment

It was noted earlier that EMDS projects can contain multiple scales of assessment. Logic models tend to be relatively scale-specific, because the nature of the questions being posed, and the way in which they are answered, both tend to change with scale. Here, let us consider how two scales of assessment can be linked.

In the context of the Chewaucan project, two scales were of interest: the reach and sub-watershedscales, and the project contains a logic model for each scale. In EMDS, the concept of logic models as networks of topics is extendable to assessments. That is, we can think of assessments as providing formal specifications for the evaluation of networks of logic models when the basic assessment problem suggests the need for multiple scales of evaluation. While the Chewaucan example is limited to two linked scales of evaluation, the idea is easily extended to multiple scales, and there is no requirement that scales be hierarchically nested. Thus, we can think of networks of models as opposed to hierarchies of models.

The Chewaucan project provides a simple example of how specifications are developed for linking scales of assessment. The basic approach requires summarizing information from one scale in a manner that makes the information applicable at another scale. In general, some sort of transformation of information is needed when moving information from one scale of evaluation to the next. In the Chewaucan project, for example, evaluations of reach condition were summarized by subwatershed as the length-weighted average of reach condition results, and the length-weighted average results were provided to the attribute table of the subwatershed layer.

## 4 Adaptive management

Since its inception, a long-term goal of EMDS development has been to provide effective decision support for the complete adaptive management process[34]. Versions 1.0 and 2.0 focused on delivery of decision support for landscape assessment. Use of the NetWeaver logic engine in these versions allowed tackling the large, abstract, and complex questions that are now typically posed in the context of ecosystem management. Feedback from the EMDS user community has consistently validated the original development team's belief that a logic-based approach, that could evaluate incomplete information and the influence of information, would be extremely useful for landscape assessment. The logic specifications developed for assessment also, in a sense, provide a backdoor into the monitoring phase of the adaptive management process. In version 3.0, the complete re-engineering of EMDS into a COM-based application also afforded the opportunity to significantly extend the system's support of the adaptive management process through integration of the new Priority Analyst component that supports the planning phase of the process.

## 5 Adaptive strategic planning

The application of logic models to assessment in the context of adaptive management is easily extended to strategic planning. In fact, the traditional approach to strategic planning begins with an identification of driving issues and an assessment of current conditions with respect to the issues[35]. Historically, strategic planning cycles have been implemented on a regular temporal cycle (e.g., the planning process of the U.S. Department of Agriculture, Forest Service). This need not be the case, however. The structure of a logic model can, in principle, encapsulate the central issues that drive a strategic planning process in precisely the same way as we have described for ecosystem assessment in the adaptive management process. If the issues identified in the current plan remain valid, and no new ones have emerged since the start of the current planning cycle, then this would suggest that there is no need for a major overhaul of the existing plan, but perhaps only minor incremental, evolutionary changes, similar to the adaptive management process.

Now, however, let us consider the situation in which a strategic forest plan does require revision, and a new assessment of current conditions has been produced. The traditional approach to strategic planning calls for the identification of a few, to several, strategic alternatives that effectively bound the decision space[35]. Ideally, the design of each alternative is responsive to the same issues originally driving the planning process, so it seems only reasonable that the alternatives are assessed in a manner consistent with that used to assess the current condition. The application of a formal logic in assessment of both current conditions and projections based on strategic alternatives can provide an effective measure of quality assurance with respect to consistent interpretation of complex information that is otherwise rather difficult to demonstrate.

Up to this point, we have considered the application of logic models to assessment of current condition and strategic alternatives. However, they also are equally applicable to evaluating the progress of plan implementation. In other words, having chosen a strategic alternative, some 5 or 10 years later, we would like to evaluate whether the plan is performing adequately. Again, it seems only reasonable to apply the same logic model to this phase of the plan.

## 6 Discussion and conclusions

Since the initial release of EMDS in 1997, it has proven to be reasonably successful as an approach to providing decision support for environmental assessment. A number of published accounts of application development with EMDS can be found both within the scientific literature (for example, refs. [25—27], but also several others) and on the internet. Its logic-based approach to accommodating the types of large, abstract problems typical of modern ecosystem management is certainly one important reason for success. Another important reason, closely related to the first, was the development team's decision to implement a very generic framework, suitable for diverse problems and scales of analysis.

While version 3.0, described here, represents a significant step in the evolution of the EMDS design since the initial release, there is still considerable room for continued development. For example, if the system is to provide comprehensive support for the adaptive management process, it will need to explicitly support the implementation phase of the process. However, provision for a new component to support testing hypotheses about results obtained from consecutive assessments would be much more significant. It is difficult to overstate the practical consequences of such a development; perhaps one of the greatest difficulties that scientists and managers have encountered in trying to effectively demonstrate adaptive management revolves around precisely this issue when the objects of management concern relatively abstract things.

The development systems for logic and decision modeling that are used with EMDS often are unfamiliar to forest managers and natural resource scientists, so readers potentially interested in using the system may have concerns about ease of learning. Similarly, there also may be concern because EMDS is implemented as an extension to ArcGIS, which itself is a powerful and complex system for geographic analysis. I have presented a number of workshops over the past eight years, and found that comprehensive instructor-led training typically requires about four days. However, EMDS also comes with a comprehensive user guide and in-depth tutorials, and quite a few users have reported these materials were sufficient to quickly master the skills required to use the system effectively. Furthermore, although EMDS is an ArcGIS extension, users are somewhat insulated from the ArcGIS environment, and need only a relatively modest understanding of GIS in order to use the system effectively. Finally, when the system is fielded as an application within natural resource organizations, there effectively are three distinct levels of user: (1) the so-called power user, who understands how to build the models, and assemble them with GIS data into a complete EMDS application; (2) an intermediate user, who does not have the skills to build the models, but who can take existing models, and assemble an application; and (3) a basic user, who simply needs to know how to run an existing EMDS application. Whereas, the comprehensive training for a power user requires about four days, the basic training only requires about four hours.

There are at least three important and practical implications of the framework. First, the logic- and decision-modeling components are designed to complement each other, and break the overall analytical process into two conceptually simpler steps. Within the logic component, the emphasis is on interpretation and synthesis. Syntheses performed in the logic component often allow the design of a smaller and simpler decision model. The emphasis within the decision component is on weighting of decision criteria and accounting for additional logistical considerations that may influence priorities for management action. Second, the EMDS framework is designed to make the concept of adaptive management practical and operational. Although the current implementation does not provide explicit support for hypothesis testing as noted earlier, this is easily implemented by users with a reasonable understanding of statistical methods. Third, as suggested under **Adaptive strategic planning**, implementation of an EMDS application in this context can add greater coherence to the overall process by effectively infusing institutional memory into the process.

Finally, the full potential of the current EMDS version has yet to be fully demonstrated. From the previous section, it is not difficult to describe a methodology for logic applications that, in principle, unifies the concepts of strategic planning and adaptive management within a single practical framework.

**Endnotes** The use of trade or firm names in this paper is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service. The EMDS system can be downloaded from http://www.fsl.orst.edu/ emds.

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