A Knowledge-Based Information Management System for Watershed Analysis in the Pacific Northwest U.S.[1]

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Abstract. The Pacific Northwest Research Station (USDA Forest Service) is developing a knowledge-based information management system to provide decision support for watershed analysis. The system includes: (1) a GIS interface that allows users to navigate graphically to specific provinces and watersheds and display a variety of themes (vegetation, streams, roads, topography, etc.) and other area-specific information (relevant regulations, existence and location of analyses, plans, etc.); (2) an analysis component that helps identify major concerns and the hierarchies of associated ecosystem processes requiring analysis; (3) a report manager that displays the history, status, and details of analyses; (4) a project manager that assists with planning and monitoring of data acquisition; and (5) a hypermedia system that provides powerful navigation tools for accessing information in various policy and procedure documents.

The analysis component contains dependency networks that link problem-solving knowledge about concerns, ecosystem processes, and data to specific landscape units. The goal-dependency approach provides a scientifically sound method for determining data requirements, as well as a basis for prioritizing, acquiring, and evaluating information for watershed analyses.

The rise of the environmental movement in the early 1960s and the concomitant increase in a sense of public responsibility for the environment (Caldwell et al. 1994) resulted in a flurry of environmental legislation in the United States (National Environmental Policy Act, Endangered Species Act, National Forest Management Act, and others). Increasing demands on managers to address complex, often contradictory laws and regulations in planning documents taxed management capabilities. At the same time, growing public distrust and dissatisfaction with management of public lands was evidenced by increasingly frequent legal challenges to resource management by fed-

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eral agencies. In the Pacific Northwest, events culminated in a series of legal challenges to Forest Service management policy with respect to the northern spotted owl (the so-called Dwyer decisions, Caldwell et al. 1994) and a series of reports sponsored by the agency (Johnson et al. 1991; Thomas et al. 1990, 1993). The net effect was to bring forest management on federal land in the Pacific Northwest to a virtual standstill by 1992.

President Clinton convened the Forest Conference in Portland. Oregon, in April 1993 in an attempt to bring all concerned parties together and break the gridlock on forest resource management in the region. The Forest Ecosystem Management Assessment Team (FEMAT) was commissioned shortly thereafter.

In its instructions to the FEMAT, the Forest Conference Executive Committee stated that the team's objectives were to identify management alternatives that "Attain the greatest economic and social contributions from the forests" consistent with meeting "the requirements of the applicable laws and regulations ...." (Thomas 1994).

The FEMAT Report (FEMAT 1993) was issued in July 1993. Despite many detractors, the FEMAT process has produced the most concrete and thorough statement to date of what is required of ecosystem management (USDA Forest Service and USDI Bureau of Land Management 1994). The Standards and Guidelines, published as an attachment to the latter Record of Decision, define a variety of land allocation types, prescribe detailed and specific management procedures for them, and establish an aquatic conservation strategy with particular emphasis on management of riparian areas. Soon after publication of the FEMAT Report, the Regional Interagency Executive Committee (RIEC) was commissioned to oversee implementation of what has come to be known as the Northwest Forest Plan.

Nineteen working groups were established under the direction of RIEC to handle various aspects of implementing the Northwest Forest Plan, including, for example, working groups on research and monitoring, information management, watershed analysis, adaptive management areas, and the adaptive management process per se. A group conspicuously missing from the RIEC working groups, however, was a system design group with responsibility to fit all the pieces together into a coherent system for analysis, planning, and management.

The objectives of this paper are to 1) describe and document the process of development team identification and organization, 2) present both short- and long-term project goals and objectives, 3) describe the overall system structure, 4) describe the methodology and subject matter areas for the various knowledge bases within the system, and 5) discuss the implications of this approach to natural resource management.

Early Team Activity

The ecosystem management decision support (EMDS) design team of the Pacific Northwest Research Station (USDA Forest Service) was organized in November 1993 to begin developing a prototype decision support system (DSS) for ecosystem management. The team (hereafter, EMDS design team) first met in February 1994. EMDS design team members had previously reviewed the FEMAT Report and numerous working group reports to RIEC as background material. The initial task was to determine what aspects of decision support for ecosystem management could benefit most from the application of decision support technologies, given the basic expectations of ecosystem management (USDA Forest Service 1992), the current state of conceptual development of an ecosystem management process (FEMAT 1993), and current technological capabilities for implementing such a process.

Focus on Watershed Analysis

Watershed analysis emerged as a particularly promising area for development. The FEMAT Report clearly identified watershed analysis as a key component of the ecosystem management process, and a first draft guide to watershed analysis[3] had just been completed, which, on review, described a reasonably well-defined process suitable for decision support system development. Moreover, a watershed analysis DSS can probably be scaled easily up to province-scale analysis (Bailey 1987).

By the end of the EMDS design team's first meeting, a conceptual model for a watershed analysis decision support system was developed and reviewed by key PNW Station and Region 6 staff. Based on favorable reviews of the EMDS design team's concepts, a detailed analysis of the watershed analysis process described in the first draft

[3] A federal agency guide for pilot watershed analysis, Version 1.0, February 1993.

guide was initiated. Briefly, the watershed analysis process described by the draft guide can be summarized as:

- Identify issues and concerns, set priorities among them, set goals and objectives for management, and formulate key questions;
- Identify ecosystem processes that require analysis;
- Set priorities among ecosystem processes of concern;
- Implement analysis modules for data acquisition and analyses;
- Describe ecosystem states and processes in the current landscape;
- Predict trends for ecosystem states and processes under alternative management scenarios; and
- Summarize analytical results and organize information for reporting on design of riparian reserves, restoration activities, transportation planning, monitoring, cumulative effects, and other activities.

Relevant to step 2, the guide contained five tables, each representing a top-level category of concern (e.g., anadromous fish). Each table contained a list of concerns, ecosystem state requirements for satisfying each concern, and an associated reference to more specific concerns. For example, a potential concern for anadromous fish was acceptable spawning sites, which were to be analyzed in terms of sufficient spawning gravel, appropriate substrate size (both of which are affected by mechanisms under substrate), and sufficient flow (which is affected by mechanisms under baseflow). Each mechanism, in turn, had an associated cause, whose state was to be assessed, and data requirements. Although the first draft guide used various terms such as concerns, mechanisms, and causes, they can all be thought of as various levels of concern, so the present example suggests a hierarchy of concerns. Accordingly, the EMDS design team decided that knowledge of relations among concerns, ecosystem processes and states, and data requirements for those processes and states could be well represented by dependency networks (Stone et al. 1986).

Project Goals and Objectives

Long-Term Perspective

The basic goal of decision support for ecosystem management is to maintain and improve forest ecosystem health and productivity by providing managers with guidance consistent with laws, regulations, and scientific principles related to ecosystem management and public values. Specific long-term objectives of the DSS project in support of this goal are to provide managers of federal forest land with a system that:

- Increases efficiency of decision processes in ecosystem analysis, planning, and management;
- Improves managers' ability to explain to the public the reasoning behind decisions;
- Ensures compliance with laws and regulations;
- Supports scientifically sound principles of ecosystem analysis, planning, and management;
- Improves managers' understanding of laws, regulations, ecosystem management principles, and public values and how they apply to analysis, planning, and management;
- Improves consistency in analysis, planning, and management within and across spatial scales;
- Integrates adaptive management into the DSS; and
- Links individual site installations of the DSS into a regional network to ensure consistency of decisions in time and space where appropriate.

The larger and more long-term objectives were addressed first because these define a larger context within which the first prototypes need to be developed if they are to evolve beyond decision support tools for isolated watershed analyses. In this larger context, many, if not most, data-based representations of the physical world cross multiple ownerships (e.g., forest types, watershed boundaries). Coordinating analysis, planning, and management activities within and between public agencies and adjacent private landowners will be essential to ensure that assumptions about effects of management scenarios are valid. Therefore, users of a DSS for ecosystem management at any particular administrative unit will need access to information managed by other units. DSSs operating at individual locations will need to be designed to operate in a network. In the DSS network, an administrative unit will have a local version of the DSS which can obtain any necessary information from other systems by telecommunication over the network. Network communication among administrative units will allow creation of explicit methods for achieving a negotiated resolution of multiple-scale decisions over time and space, a capability required to realize objectives 6 and 8. As noted earlier, part of the attraction of developing a prototype for the watershed scale is that we anticipate that it can be easily scaled up to operate at the level of ecosystem provinces (sensu FEMAT). This consideration is relevant to objective 6.

Stages of Implementation

The scope and complexity of implementing a DSS to support ecosystem management are so great that the only feasible approach to the overall task is to decompose it into a number of relatively discrete, manageable stages. Although the precise ordering may be subject to change over the development cycle, the steps are currently envisioned as:

- development of knowledge-based information management to support assessment of current ecosystem condition at the watershed scale;
- extension of information management to province-level (Bailey 1987) assessment with provision for communication between scales;
- integration with predictive systems such as the Modular Modeling System (Leavesley et al. 1995) to allow assessment of future system states under alternative management scenarios (watershed and province level); and
- knowledge-based support for adaptive management planning, including design and operation of monitoring systems (Bormann et al. 1994).

Stage 1 Implementation

In stage 1 of implementation, the immediate objective is to provide knowledge-based information management for watershed analysis. The first prototype DSS now under development is intended to provide a foundation that can easily be built upon to eventually realize the project's long-term objectives. We view the development of a competent information management system as requisite for many of the long-term objectives. The objectives for this stage of implementation are to:

- graphically orient the user to the landscape and provide access to GIS and other databases that provide the user with background information for their specific watershed analysis project;
- provide data management and analysis for high-level concerns (e.g., suitable spawning habitat for salmon species) identified by a user; including
  - identify and rank data required for a watershed analysis;
  - obtain existing data,
  - provide an assessment of intermediate ecosystem states associated with the concern as well as an overall assessment of the top-level concern; and
  - graphically display results of assessments;
- facilitate managing a watershed analysis process with tools for project management;
- facilitate reporting results of a watershed analysis; and
- provide reference material that helps a user performing watershed analysis and explains the rationale for how an analysis was performed and any conclusions that are drawn.

These objectives translate into basic functional requirements for system design in a straightforward manner. Basic functional requirements, in turn, lead to identification of a prototype system architecture (Figure 1). The user interacts directly with five subsystems (GIS, knowledge base manager, report manager, project manager, and hypertext manager) which operate in a client/server architecture to provide watershed analysis reports. Below, we briefly summarize key features of system architecture. More detailed and complete discussion is presented later (System Functions and Logical Structure).

GIS

The GIS component, implemented in ArcView, includes both display and database management functions.[4] The database management subsystem within ArcView accesses a data catalog to locate databases needed for display and analysis (Figure 1). Maps and tables can be produced independently of analyses performed by the knowledge base manager, and can help orient the user to their specific watershed analysis project prior to actually conducting analyses.

Knowledge base manager

This component, implemented in KnowledgePro for Windows, is the primary analytical subsystem and is referred to in later sections as the analysis subsystem. The knowledge base manager accesses permanent knowledge bases (meta databases) and provides the user with browsing and editing functions used to conduct an analysis. Instantiated versions of the knowledge bases are stored, as system status files specific to a project, and specify data

[4] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

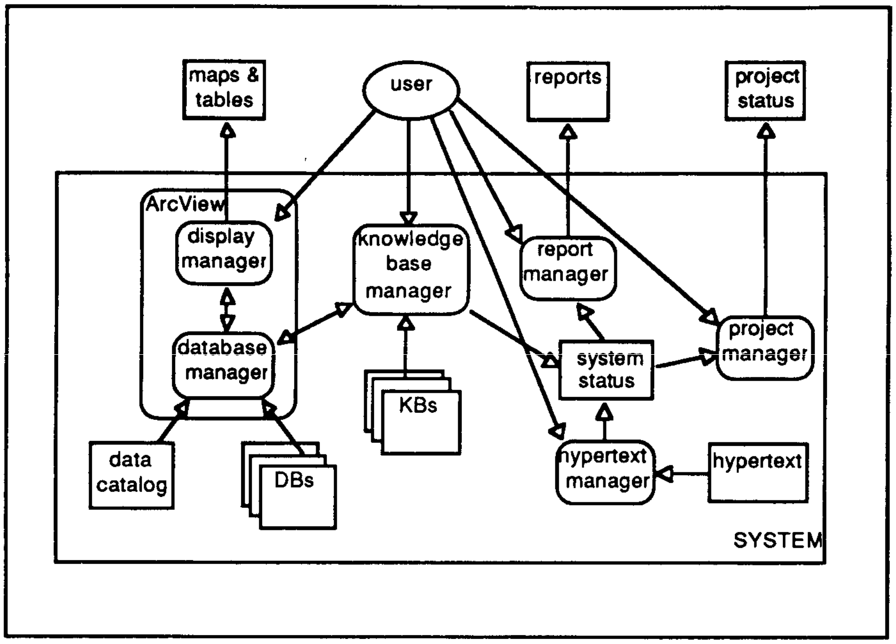

Figure 1. *Main subsystems of the ecosystem management knowledge base system. Rounded rectangles indicate major subsystems, while plain rectangles indicate data stores such as databases (DBs) and knowledge bases (KBs). The user interacts directly with each subsystem. System operation is based on a client/server architecture. The data catalog is used by the database manager subsystem of the GIS subsystem to locate databases needed for either display or analysis.*

requirements to the knowledge base manager, which accesses the ArcView database manager to retrieve data sets required for analyses (Figure 1). The knowledge base manager also specifies new GIS themes derived from an analysis that the database manager adds to its data catalog.

Knowledge Bases

Dependency Networks as Metadata

One working definition of metadata is that it is data about data. For example, a database that stores information about the location, reliability, data collection protocols, and originators of inventory data (stored in a separate database) is information *about* data, and hence can be considered metadata. In a broad sense, this would be any data involved in the interpretation of other data. Metadata can also exist in the form of rules or procedures used to arrive at the interpretation of data. In the narrow sense, the analysis DSS's metadata are dependency networks (Stone et al. 1986) that makeup its knowledge base. These networks formalize current, available knowledge about watershed-level phenomena. The dependency networks can be used by analysis teams to identify data needs and assist in the interpretation of field-derived data (Nash et al. 1992).

Use of Dependency Networks

Dependency networks are used in the Analysis subsystem described subsequently to formalize current scientific understanding of the (hierarchical) relations among concerns, ecosystem processes, and data requirements. Dependency networks are composed of objects (goals, subgoals, and data links). Goals and subgoals can be weighted and their truth value determined via fuzzy logic if necessary. Uses of dependency networks in our context are to:

- identify data requirements for an analysis;
- rank missing data in order of relative importance to the analysis; and
- report the truth value of conclusions about ecosystem states and processes given existing data.

In particular, we are using the NetWeaver application, developed at Penn State University (Saunders et al. 1989, 1990), for design of dependency networks.

Dependency Networks for Watershed Analysis

In addition to the general system analysis and design activity of the EMDS design team, the team is also organized into three subteams that are constructing dependency networks for six broad topic areas:

- terrestrial vegetation
- terrestrial fauna
- anadromous fish
- riparian system,
- surface water supply
- roads and structures

For each topic area, a subteam of two knowledge engineers is working with two to three scientists and resource specialists to develop a prototype network. On completion, prototype networks will be reviewed by a larger panel of eight to 10 scientists and specialists.

Analysis and Design Methods

Object-oriented methods for analysis and design are being used for system development. In more traditional methods of top-down structured design, analysis and design are based on functional decomposition of problems; these methods evolved to support programming languages such as FORTRAN and COBOL. In contrast, object-oriented analysis and design have evolved to support languages such as Smalltalk, Object Pascal, and C++, in which problem decomposition is based on the concept of objects (Booth 1994). Object-oriented problem decomposition offers a number of advantages over the functional approach:

> Object-oriented decomposition yields smaller systems through the reuse of common mechanisms, thus providing an important economy of expression. Object-oriented systems are also more resilient to change and thus better able to evolve over time, because their design is based upon stable intermediate forms. Indeed, object-oriented decomposition greatly reduces the risk of building complex software systems, because they are designed to evolve incrementally from smaller systems in which we already have confidence (Booth 1994).

Rapid prototyping, with short cycles for analysis, design, and implementation, is fundamental to object-oriented methods and also fits well with knowledge engineering methods being used by the EMDS design team for development of the dependency networks. In the following section, we use Booth diagrams (Booth 1994) to graphically illustrate the physical and logical structure of the system. System diagrams are not intended to be comprehensive. For class diagrams in particular, we show only the most important high-level classes and relations.

System Functions and Logical Structure

Major elements of the system's logical structure include representations of the GIS, Analysis (knowledge base manager), Report Manager, Project Manager, and Hypertext Manager subsystems (Figure 1).

GIS

Functional description

ArcView is used as a navigation and information-display tool (Figure 1), and is the primary access to other EMDS subsystems through its application menus. ArcView is also the system's primary database manager, maintaining and querying a data catalog that is used to identify file names, records, and fields and their physical locations given data requirements for display or analysis (Figure 2). ArcView physically contains a table of contents that allows the user to select themes for display on the presently displayed map. Themes and their attributes are contained by reference. The analysis subsystem uses ArcView to display new themes generated by analyses.

Interface

ArcView provides a GIS interface that allows the user to visually navigate to specific provinces and watersheds and display a variety of GIS themes (vegetation, streams, roads, topography, etc.) and other area-specific information (relevant regulations, existence and location of analyses, plans, etc.).

Existing data for display consists of GIS data stored in Oracle data sets on workstations and other, non-GIS data stored in Microsoft Access or Borland Paradox databases on PCs. In the first EMDS system prototype, database access is limited to local area networks. Later implementations will provide for data access over a wide-area network once the required communication infrastructure is in place in at least some sites in Region 6. Basic GIS capabilities as part of the primary user interface are provided to orient watershed analysis teams to the analysis situation.

Because ArcView 2.0 is already a full-featured, relatively mature GIS application, system design involves relatively little modification to the basic ArcView environment. The only significant change being introduced is to simplify the user interface by hiding application functions not directly related to requirements for overall system functionality. However, the modified environment will still provide optional access to the full set of ArcView features.

Data catalog

USDA Forest Service Region 6 and the Siuslaw National Forest are now in the process of collecting and organizing descriptions of all Oracle workstation and PC databases (Microsoft Access and Borland Paradox) considered potentially useful to the EMDS system.

ArcView functions as the system's central data server, handling requests from other subsystems (discussed further in the following sections), querying appropriate databases, and passing the required data back to the client subsystem (Figure 2).

Communication

All other subsystems can be invoked from ArcView menus. The ArcView database manager communicates directly with the Analysis subsystem, receiving data requests from the Analysis subsystem and passing back requested data. In addition, dependency network nodes from the Analysis subsystem can be selected for addition to ArcView's table of contents (Figures 1 and 2). Within ArcView, evaluated goal states for a selected node are displayed as a new theme, with access to relevant attributes also managed by ArcView. Communication with the Report Manager subsystem is only indirect, being mediated by the tagger object discussed later.

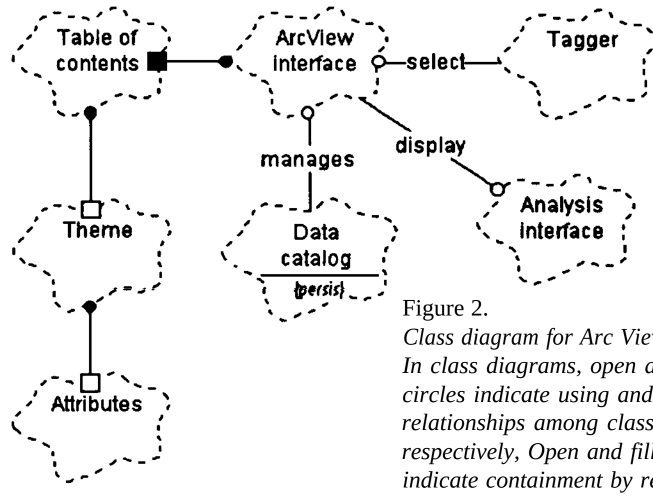

Figure 2.
Class diagram for Arc View relations, In class diagrams, open and filled circles indicate using and has-a relationships among classes, respectively, Open and filled squares indicate containment by reference and value, respectively, for has-a relationships. Arrows indicate inheritance relationships,

Analysis

Functional description

The Analysis subsystem (knowledge base manager in Figure 1) uses dependency networks to represent the current state of ecosystem processes and watershed properties and impacts of watershed-level activities on these processes and properties. It provides a link between the goals and objectives of managers and specific on-the-ground questions that need to be answered to adequately assess those objectives. Later implementations will expand the scope of analysis to include the province level, and provide for integration between the two levels of analysis.

The Analysis subsystem:

- helps identify ecosystem processes requiring analysis;
- assists in selecting appropriate subsets of analyses, identifying and ranking data requirements and evaluating ecosystem states; and
- provides information to the Project Manager and Report Manager subsystems for tracking progress of and documenting an analysis.

The Analysis subsystem includes a browsing facility to let the users navigate through the networks in an intuitive way so users can examine the structure of dependencies and select appropriate goal nodes for inclusion in an analysis (Figure 3).

The users have the option of ignoring irrelevant concerns, in which case they are prompted to provide documentation that explains the rationale for the decision. Each goal node also provides five types of documentation:

- authorities who were the source of information on how the node's relations were defined;
- literature citations;
- explanatory information about the role of the node in the network structure;
- comments from the watershed analysis team; and
- assumptions about ecosystem processes that are relevant to the node.

Interface

The interface for the analysis subsystem consists of a set of windows and other screen objects that allow the user to perform specific operations on the network hierarchy:

- open network and navigate to (browse) any node in the hierarchy by one of two or three methods;
- load, run, and save an analysis profile;
- edit items within the analysis profile (i.e. activate or de-activate links in the analysis profile, and/or enter values for analysis profile objects intermediate between data and the ultimate metadata node);
- view associated short descriptive or explanatory hypertext or related passages in Hypermedia Reference subsystem documents;
- check availability and timestamp of data for data links in the knowledge net;
- tag anything associated with a data link or subgoal (tiles, hypertext, etc.) for inclusion in an analysis report; and
- fetch existing data.

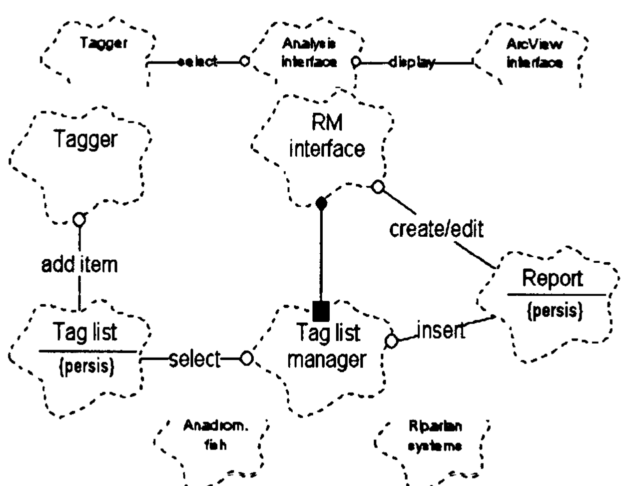

Figure 3.
Class diagram for Analysis relations. In class diagrams, open and filled circles indicate using and has-a relationships among classes, respectively. Open and filled squares indicate containment by reference and value, respectively, for has-a relationships. Arrows indicate inheritance relationships.

Browsing and editing dependency network nodes, and running the Net Weaver engine to fetch data assists the user in identifying the availability of data and prioritizing acquisition of missing data. The process of browsing and editing generates a project-specific analysis profile (knowledge base) via pruning:

- user selects goals and subgoals that are related to concerns about ecosystem processes.
- the NetWeaver engine identifies all connected (related) higher- and lower-level concerns.
- user browses and prunes the dependency nets to ignore irrelevant or uninteresting concerns, resulting in a final pruned dependency net.

Communication

The Analysis subsystem is called from ArcView by selecting the Analysis menu item. Most communication between the two subsystems involves requests from the Analysis subsystem to ArcView:

- requested data to satisfy data requirements of knowledge base data links and
- requests to display dependency network node states as new GIS themes (Figures 1 and 3).

All dependency network nodes have a set of five text objects as attributes of the node. The text objects can contain hypertext references to material in the Hypertext Manager subsystem.

The Analysis subsystem does not communicate directly with either the Project Manager or Report Manager subsystems. However, analysis profiles are available to both of these other subsystems as NetWeaver scripts through the tagger utility described later.

Network navigation and editing

Navigation through the networks, and editing links and node states, can be done in either text mode or graphic mode. Both modes display two child windows within the display area of the main Analysis application window:

- the hierarchy window displays network topology as either an indented hierarchical list of nodes in text mode or a graphical map of nodes in graphic mode;
- the information window displays information about the currently selected node in the hierarchy window, and contains screen objects that provide additional information and control over some aspects of the hierarchy display.

Running an analysis

The run command in the Analysis subsystem calls the NetWeaver dynamic link library (DLL) with instructions to evaluate the network. The full evaluation process involves the following steps:

- Run command in Analysis initiates request to DLL to evaluate network;
- DLL traces active links among goal dependencies;
- DLL identities unsatisfied data links and passes data requirements to Analysis;
- if necessary, Analysis issues data request to ArcView;
- ArcView interrogates data catalog for source of data, and uses SQL calls to appropriate databases;
- ArcView returns data values to Analysis;
- Analysis returns data values to NetWeaver DLL;
- DLL updates data links;
- DLL re-evaluates network and returns updated states of nodes to Analysis.

Checking availability and timestamp of data

On completing a run, the user can view the status of an analysis. A status window displays a table with a record for each goal node and data link. A record includes:

- node name
- percent of data requirements met
- priority (relative contribution of this node's missing data to total missing data)
- total number of antecedents
- number of immediate antecedents
- total number of dependents
- number of immediate dependents
- date of most recent data source
- date of oldest data source

Some of the functions available for the status window are:

- select record;
- view the list of values associated with selected record (note that, in general, a data link processes a list of values, so each goal also has a list of states or outcomes);
- sort records by priority of missing data; and
- view only records with missing data.

Project Manager

Functional description

Through its Project Manager subsystem, the system provides a project summary of particular interest to line officers. The core functions of the Project Manager subsystem are provided by a higher-level dependency network that polls the set of dependency networks generated by the Analysis subsystem and maintained in the system status files (Figure 1). Its function is to assist with planning and monitoring data acquisition, and tracking and documenting the progress of an analysis by using analysis profiles generated by the dependency networks.

The first prototype implementation will be limited to summary reporting features. However, these should be valuable to both line officers and watershed analysis teams. In the second or later implementation, we will add tools to assist with scheduling of expenditures of money and personnel time, so that data collection projects can be timed and coordinated to make the best use of operational resources. This type of operational tracking is essential to creating informative and credible reports, but this full implementation is not feasible for the expected delivery schedule of the first prototype.

Communication

Access to the Project Manager subsystem is provided through a menu item in ArcView. Optionally, while viewing the analysis summary, the user can invoke the Analysis subsystem in view mode for a more detailed examination of data requirements.

The Hypertext Manager subsystem can be called from a menu item on the Project Manager menu bar. The Project Manager does not communicate directly with the Report Manager, but its output files are available to the Report Manager via the tag list manager, described later.

The summary reports

- trueness value associated with each top-level goal that has been selected for analysis and
- a synthesis of data requirements from all of the separate nets.

Hypertext Manager Subsystem

Functional description

The Hypertext Manager subsystem provides navigation tools for accessing information in the FEMAT Report, the Record of Decision, and Standards and Guides. The initial content of the subsystem could easily be expanded to include the Watershed Analysis Handbook now under development by the Region 6 Watershed Analysis Coordination Team. Legal references such as text of NEPA and NFMA can also be added in the second implementation, if that is desirable.

Communication

Direct access to this subsystem is provided through

- menus of other subsystems and
- embedded hypertext in hypermedia objects managed by other subsystems.

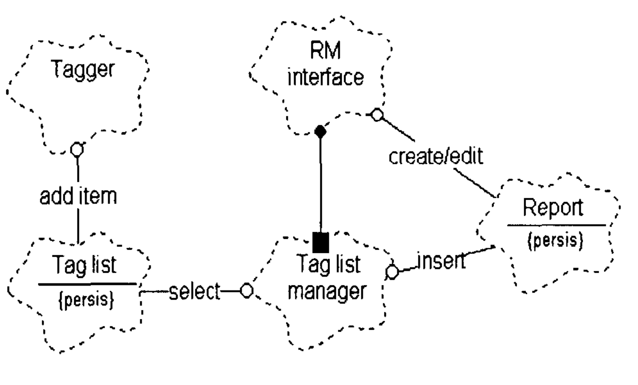

Figure 4.
Class diagram for Report Manager relations. In class diagrams, open and filled circles indicate using and has-a relationships among classes, respectively. Open and filled squares indicate containment by reference and value, respectively, for has-a relationships. Arrows indicate inheritance relationships.

In the first prototype, direct access to the Hypermedia Reference subsystem is provided through menus in all other subsystems. In the second prototype, we plan to provide constrained, intelligent search capabilities within the Analysis subsystem to access more specific information in the FEMAT report, Record of Decision, Standards and Guides, based on a user's current location in the dependency networks.

Report Manager

Functional description

The Report Manager for the first prototype will most likely be implemented in KnowledgePro, using a Microsoft Word DLL currently in production. In later prototypes, we also plan to introduce additional knowledge-based functionality that provides a template for the seven-step watershed analysis process.

The Report Manager subsystem assists with assembling numerous pieces of information into a coherent report (Figure 4). The Report Manager handles display of project history and status, and other details of an analysis, and provides the user with tools to assemble reports of an analysis, which may include maps, information from the project log, status and project management files, as well as hypertext excerpts from items in the Hypermedia Reference subsystem.

The system includes a globally accessible tag utility that can optionally be used to add the contents of any system display window to the tag list. A key tool in the Report Manager that complements the tag utility is a tag list manager that is used to browse among, and select items from, a list of items for inclusion in a report.

Communication

The ArcView subsystem provides direct access to the Report Manager through a menu item. Documents from the Hypermedia Reference subsystem can be easily incorporated into the report to provide expanded explanation for the analysis process, or accessed as an on-line reference by a watershed analysis team as an aid to conducting an analysis. Other subsystems do not communicate directly with the Report Manager, but many of their display window contents and all output files are available to the Report Manager via the tag list manager discussed below.

Contents of a watershed analysis report

Watershed analysis reports include both text and graphics. Graphics include:

- maps generated by ArcView;
- graphic images from the Hypermedia Reference subsystem; and
- possibly other graphic images.

Text sources for reports include:

- hypertext from the Hypermedia Reference subsystem;
- text from the annotation function group in the Analysis subsystem;
- individual analysis profiles;
- analysis status reports from the Analysis subsystem; and
- project status from the Project Manager subsystem.

Tag utility

Tagging information is performed by a utility that is accessible from all subsystems. The function of the tag utility is to mark any information in a display window of any subsystem for possible inclusion in an analysis report (Figure 4). The most general approach for implementing the tag function requires two files:

- a tag data file that stores both data and pointers to data and
- a tag list file that contains pointers to tag data tile records and other descriptive information about a tagged item.

A tag list file record contains:

- a pointer to a tag data file record;
- brief description for identifying content;
- the time stamp of the source data; and
- a time stamp indicating when the information was added to the tag tile.

Tag list manager utility

The tag list manager utility is used to browse, review, arrange, and preview information that has been assembled by the tag utility. Functions of the tag list manager are:

- display contents of the tag list file;
- check time stamp of tag list items against data source;
- view selected tag list item;
- arrange order of tag list items;
- insert selected item(s) at current location in report document; and
- insert complete contents of the tag file in report document according to tag list order.

The check-time-stamp function:

- can be invoked by the user to perform a comprehensive check of all items in the tag tile (reports all items that may need updating) and
- executes automatically whenever the insert functions are executed unless the user has turned off autochecking.

Present Status and Future Possibilities

Concepts of ecosystem integrity and sustainability are closely intertwined with human values (Kay 1993). A basic premise of ecosystem management is that combined application of knowledge and technology can be used to promote desirable ecosystem conditions that benefit both the environment and social and economic systems (Salwasser 1994). Bormann et al. (1993), describing a framework for management of sustainable ecosystems, have defined ecological sustainability as the intersection of societal values and ecological capacity. Inherent in each of these views is the notion that ecosystem sustainability cannot be adequately addressed apart from societal values.

The DSS for watershed analysis that has been described clearly encompasses only a few aspects of a full ecosystem management process (Bormann et al. 1994); it provides a knowledge-based information management system that assists with data acquisition and evaluation of ecological integrity. However, the scope and complexity of an ecosystem approach to natural resource management (Franklin 1994) highlight the basic need to acquire, access, operate on, and manage very large quantities of very diverse information. In this respect, the

DSS provides art essential foundation upon which to build a more comprehensive decision support system for ecosystem management. Also, insofar as the hypermedia capabilities of the system enhance the ability of managers to effectively communicate the rationale behind an analysis process and its outcomes, the DSS can make a useful contribution to the dialog that is essential to the adaptive management process of reconciling societal wants with ecological reality.

With object-oriented system development, we envision short development cycles in which incremental enhancements to the original prototype are introduced at about six-month intervals. A likely near-term enhancement is the integration of groupware technologies that further enhance such dialog (Fox, TERRA Lab, Fort Collins, personal communication). In discussing the Report Manager subsystem, we mentioned incorporating knowledge-based support for the full watershed analysis process described in the Watershed Analysis Guidebook, now being developed by Forest Service Region 6. The Guidebook itself will likely be added to the Hypermedia Reference subsystem. This general approach to knowledge-based information management system development has enormous relevance to other natural resource management arenas. Rapid prototyping, coupled with scrupulously maintained documentation of heuristics, technical literature, relevant legislation, and data lineage will permit early implementation of decision support products that can continue to grow and improve while being used.

In the longer term, we envision building upon this basic information management foundation needed to support watershed analysis to eventually provide knowledge-based decision support for the full adaptive management process. A logical first step in this longer-term development, which also completes development of the watershed analysis component, is integration of a system for process models used to consider alternative future management scenarios (Leavesley, USGS, Boulder, personal communication). Numerous other ongoing development efforts may eventually be integrated into the foundation system. In such an evolutionary process, it is useful to keep in mind Booth's (1994) advice: the analysis and design of complex systems require a clear architectural vision to sustain long-term development.

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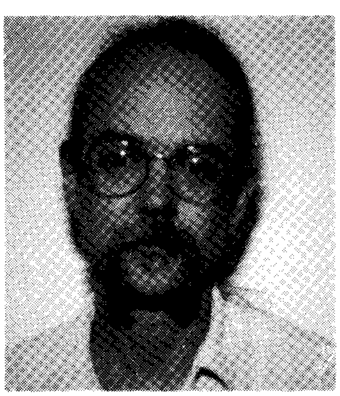

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