

**Knowledge-based Information Management for Watershed Analysis in the Pacific  
Northwest U.S.**

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**Abstract**

We are developing a knowledge-based information management system to provide decision support for watershed analysis in the Pacific Northwest region of the U.S. The system includes: (1) a GIS interface that allows users to graphically navigate to specific provinces and watersheds and display a variety of themes and other area-specific information, (2) an analysis component that helps identify major concerns and the hierarchies of associated ecosystem processes requiring analysis, and assists the user in selecting an appropriate subset of analyses and in identifying and prioritizing data requirements and their sources, (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 access to information in various policy and procedure documents. The core of the system is the analysis component which contains dependency networks that link problem-solving knowledge about concerns, ecosystem processes, and data to

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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.

## **1. Introduction**

This paper summarizes our object-oriented approach to analysis and design of a knowledge-based information management system that provides decision support for forest ecosystem management. Our initial task was to determine what aspects of decision support for ecosystem management could benefit most from application of decision support technologies, given 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. Watershed analysis emerged as a particularly promising area for development. The FEMAT Report clearly identified watershed analysis as a key component of ecosystem management, and a first draft guide to watershed analysis had just been completed, which described a reasonably well defined process suitable for decision support system development. The watershed analysis process described by the draft guide can be summarized as:

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

### *1.1 Long-term Project Goals and Objectives*

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:

1. Increases efficiency of decision processes in ecosystem analysis, planning, and management;
2. Improves managers' ability to explain the reasoning behind decisions to the public;
3. Ensures compliance with laws and regulations;
4. Supports scientifically sound principles of ecosystem analysis, planning, and management;
5. Improves managers' understanding of laws, regulations, ecosystem management principles, and public values and how they apply to analysis, planning, and management;

6. Improves consistency in analysis, planning, and management within and across spatial scales; and
7. Integrates adaptive management into the DSS.

### *1.2 Stage 1 implementation*

The scope and complexity of implementing a DSS to support ecosystem management are so great that the only feasible approach is to decompose the task into a number of relatively discrete, manageable stages. In stage 1 of implementation, our objective is to provide knowledge-based information management for watershed analysis. The prototype DSS now under development will provide a foundation that can easily be built upon to eventually realize the project's long-term objectives. The development of a competent information management system is a requisite condition for many of the long-term objectives. The objectives for stage 1 to:

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

Object-oriented methods for analysis and design are being used for system development. 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 design team for development of the dependency networks. In later sections, 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.

## **2. Knowledge Bases**

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.

In addition to general system analysis and design activity, the design team is also organized into three subteams that are constructing dependency networks for terrestrial vegetation, terrestrial fauna, anadromous fish, riparian systems, surface water supply, and effects of roads and structures on stream.

### **3. 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 (Fig. 1).

#### *3.1 GIS*

##### *3.1.1 Functional Description*

ArcView is used as a navigation and information-display tool (Fig. 1), and is the primary access to other 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 (Fig. 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.

##### *3.1.2 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 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 US Forest Service Region 6. Basic GIS capabilities as part of the primary user interface are provided to orient watershed analysis teams to the analysis situation.

##### *3.1.3 Data Catalog*

US 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 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 (Fig. 2).

## 3.2 Analysis

### 3.2.1 Functional Description

The Analysis subsystem (knowledge base manager in Fig. 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, respectively.

The Analysis subsystem includes a browsing facility to let the user 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 (Fig. 3). The user has 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, including, for example, authorities who were the source of information on how the node's relations were defined, literature citations, and explanatory information about the role of the node in the network structure.

### 3.2.2 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,
- 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 (files, hypertext, etc.) for inclusion in an analysis report, and
- fetch existing data.

Browsing and editing dependency network nodes, and running the NetWeaver 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:

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

### *3.2.3 Running an Analysis*

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

1. Run command in Analysis initiates request to DLL to evaluate network,
2. DLL traces active links among goal dependencies,
3. DLL identifies unsatisfied data links and passes data requirements to Analysis,
4. if necessary, Analysis issues data request to ArcView,
5. ArcView interrogates data catalog for source of data, and uses SQL calls to appropriate databases,
6. ArcView returns data values to Analysis,
7. Analysis returns data values to NetWeaver DLL,
8. DLL updates data links,
9. DLL re-evaluates network and returns updated states of nodes to Analysis.

### *3.3 Project Manager*

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 (Fig. 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. 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.

### *3.4 Hypertext Manager Subsystem*

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.

### *3.5 Report Manager Subsystem*

#### *3.5.1 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 7-step watershed analysis process.

The Report Manager subsystem assists with assembling numerous pieces of information into a coherent report (Fig. 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.

#### *3.5.2 Contents of a Watershed Analysis Report*

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

1. maps generated by ArcView,
2. graphic images from the Hypermedia Reference subsystem, and
3. possibly other graphic images.

Text sources for reports include:

1. hypertext from the Hypermedia Reference subsystem,
2. text from the annotation function group in the Analysis subsystem,
3. individual analysis profiles,
4. analysis status reports from the Analysis subsystem, and
5. project status from the Project Manager subsystem.

#### *3.5.3 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 (Fig. 4). The most general approach for implementing the tag function requires two files:

1. a tag data file that stores both data and pointers to data, and

2. a tag list file that contains pointers to tag data file records and other descriptive information about a tagged item.

A tag list file record contains:

1. a pointer to a tag data file record,
2. brief description for identifying content,
3. the time stamp of the source data, and
4. a time stamp indicating when the information was added to the tag file.

### 3.5.4 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:

1. display contents of the tag list file,
2. check time stamp of tag list items against data source,
3. view selected tag list item,
4. arrange order of tag list items,
5. insert selected item(s) at current location in report document, and
6. 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 file (reports all items that may need updating), and also executes automatically whenever the insert functions are executed unless the user has turned off autochecking.

## 4. 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 an 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 6-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.

In the longer term, we envision building upon the 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 on-going 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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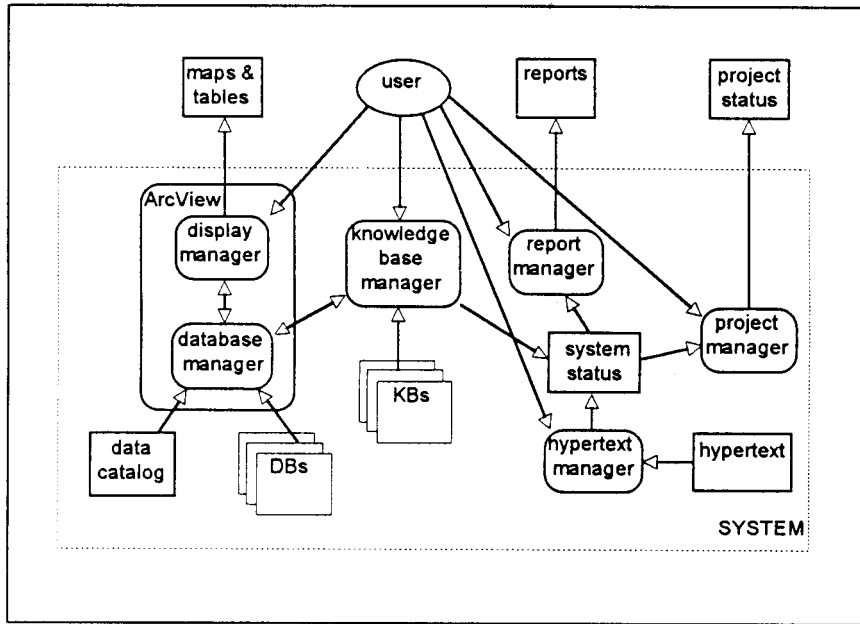


Figure 1. Main subsystems of the ecosystem management knowledge base system. Rounded rectangles indicate major subsystems, while plain rectangles indicate data stores such as databases (DBs) and knowledge bases (KBs). The user interacts directly with each subsystem. System operation is based on a client/server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

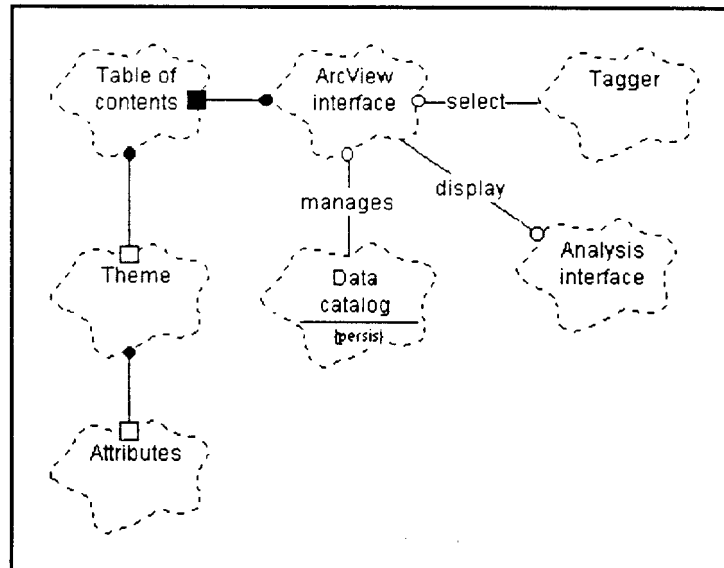


Figure 2.. Class diagram for ArcView relations. In class diagrams, open and filled circles indicate using and has-a relationships among classes, respectively. Open and filled squares indicate containment by reference and value, respectively, for has-a relationships. Arrows indicate inheritance relationships.

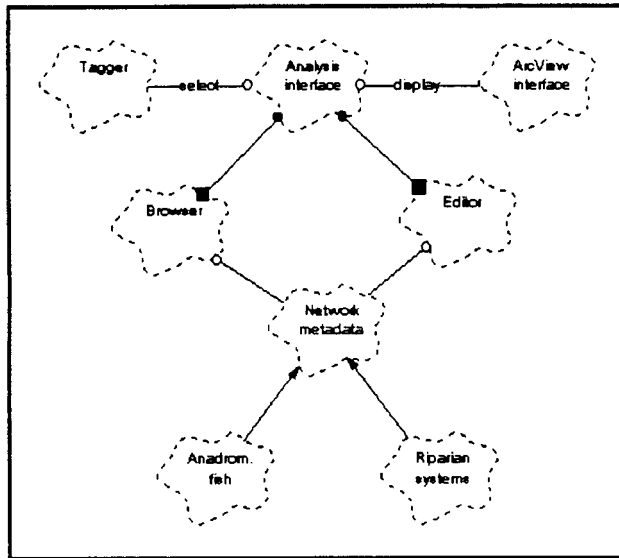


Figure 3. Class diagram for Analysis relations. See Fig. 2 capture for an explanation of notation.

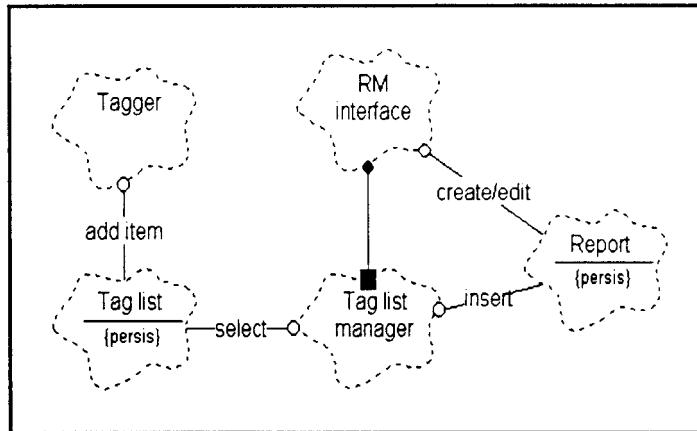


Figure 4. Class diagram for Report Manager relations. See Fig. 2 capture for an explanation of notation.

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