Natural Resource Modeling in the Geographic Information System Environment

Kevin M. Johnston
Prime Computer, Inc., Prime Park, Natick, MA 01760

ABSTRACT: While hardware and software for Geographic Information Systems (GIS) have improved exponentially, implementation of this technology for management purposes has grown linearly. Many natural resource planners now recognize the potential value of, and have access to, GIS capabilities, but often find little direction for effectively manipulating their data. This study explores the creation and implementation of a land management model developed for a Canadian timber company. Submodels were created to address visual quality, landscape ecology, potential natural vegetation, fire management, wind management, and timber production and economics. The submodels were synthesized by a main model into a final map designed to allocate resources as prescribed by management objectives. Different management scenarios could be run quickly, thus allowing a manager to analyze many management alternatives before selecting the alternative that would be most suitable. Although improved timber management was the principal objective of this study, the model was designed to be flexible enough to meet other management objectives as well.

INTRODUCTION

BECAUSE MOST Geographic Information Systems (GIS) are in their infancy, a large proportion of time is currently expended on data base creation. Users are often limited temporally from developing complex applications models and, therefore, frequently rely on extremely simple combinations of data to create output products such as land management plans. The computer allows us to create and store as many layers of data or maps as we desire. We are often, however, faced with the difficult task of developing a process or a model for selecting and intergrating the tremendous amount of data and large number of overlays into a single output to aid in decision making. This paper will address such problems within the context of a study whose focus was the development of a land management model that could integrate several submodels (models created to analyze individual management objectives, such as visual quality and fire management). The methods by which the submodels were implemented on a specific site will also be addressed.

The study, an academic project completed by the author at the Harvard Graduate School of Design, was carried out for the Fraser Timber Company of Edmundston, New Brunswick, Canada. The company provided a study site and technical aid. Timber management was the central management objective of the study, but the model proved flexible enough to have visual quality, landscape ecology, potential natural vegetation, fire management, or wind management as the central management objective. The principles that guided construction of the model should aid in the development of models for other management objectives and may be applicable in urban as well as natural environments.

BACKGROUND

The majority of models currently developed for natural resource planning are designed to address one specific land management objective at a time (for example, visual quality or wildlife). Foresters, however, have long recognized the potential of land to support many (sometimes conflicting) land management objectives within a single area. The "multiple-use concept" was discussed as early as 1906. In a letter to Chief Forester Gifford Pinchot, dated 1 February 1906, Secretary of Agriculture James Wilson wrote:

> In the administration of the National Forests it must be clearly borne in mind that all land is to be devoted to its most productive use for the permanent good of the whole people. . . . (Brockman and Merriam, 1973).

The question for land managers, of course, is "What is the *most productive use* on a given site?"

Not until passage of the Multiple Use/Sustained Yield Act (P.L. 86–517) in 1960 was the Forest Service officially placed in charge of the protection, management, and development of national forest resources for timber, outdoor recreation, water, wildlife, and forest purposes. But even then, the Forest Service was not provided with any direct guidelines for implementation, which forced the multiple-use concept to remain little more than an objective.

Goals such as those expressed by Wilson have nonetheless influenced many well-known natural resource management models, including the models of the Forest Service (1974, 1977) and the Bureau of Land Management (1980) and, more important, the models developed by McHarg (1971), which use the map overlay technique. Evolving computer technology has increased computational speeds. With the advent of GIS technology, complex analysis between layers or maps has become possible. This fact has led to changes in a number of resource management models. Nonetheless, timber management alone, because of its economic importance and deep roots in the social structure, continues to be the dominant underlying objective of most forest resource management models.

OBJECTIVES

The main computer model developed in this study is designed to integrate the results (suitability maps) derived from a set of six submodels* (Figure 1), each of which is directed toward a specific land management objective. The first submodel, which evaluates visual quality, explores the manner in which a user will visually experience the features of a study site, and determines the visual importance of each area in a study site to a user. The landscape ecology submodel analyzes the structure, function, and interrelationships of ecosystems to optimize the spatial allocation of a site's natural resources (Forman and Godron, 1986). By examining the environmental characteristics of a site, such as soil type and slope, the potential natural vegetation submodel can determine the optimal vegetation species for each area in a site. The fire management submodel identifies the areas where fires are most likely to occur and the areas to which fires would spread most rapidly, and determines the relative potential intensity of a fire within each area of the site. Through investigation of the types of vegetation found on a site, as well as their locations and the attributes of their locations, the wind management submodel can establish which areas of a site are most susceptible to windthrow damage. The final submodel,

*The steps involved in constructing each of the submodels will not be covered in this paper, but are described in Johnston (1986).

0099-1112/87/5310–1411$02.25/0
©1987 American Society for Photogrammetry and Remote Sensing

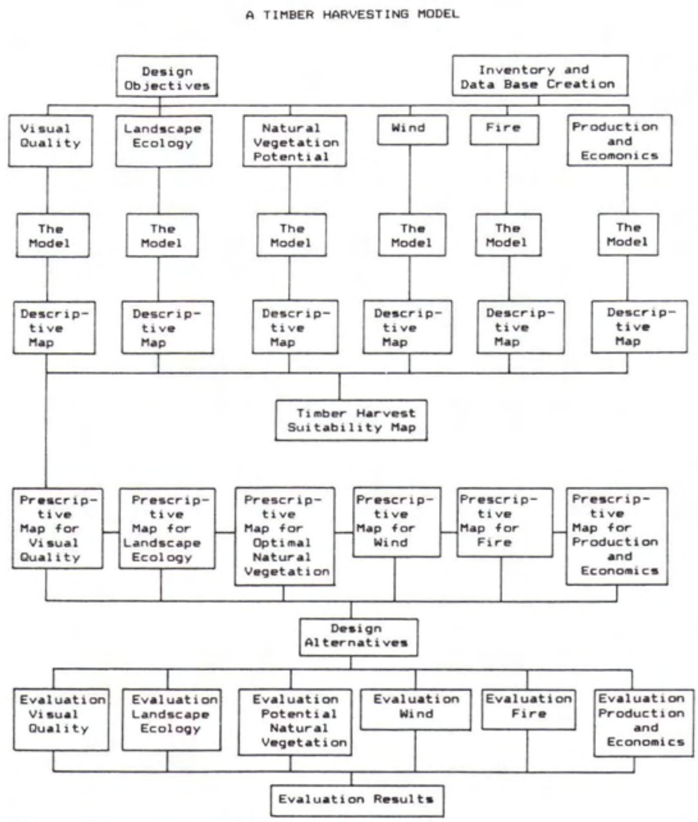

FIG. 1. Flow diagram of the main model.

representing the production and economics land use, ascertains how profitable each area of a site will be for logging.

The purpose of the main model was to provide land-use managers with the flexibility to test a variety of management scenarios† and objectives and the opportunity to examine how the results might vary. A built-in system of evaluation, which will indicate the influence of each scenario or objective on a site, aids managers in selecting the scenarios that would best meet their needs, and in determining scenarios that should be explored further. In the future the main model will be used on a type of site that differs markedly from the site examined in this study in an effort to ascertain ways in which to impart a degree of universality to the model. The model was constructed so that it could be altered to meet the individual needs of different landscapes.

METHODS

Several computers and software packages were used in the study. ODYSSEY, a vector-based system developed at the Harvard Laboratory for Computer Graphics, was used for all digitizing and some mapping. The Map Analysis Package (MAP), a system that uses a raster-based data structure, was used for all data analysis. Other software programs developed at the Harvard computer graphics laboratory were used for such tasks as converting vector maps to raster and creating computer graphics displays.

A test site on the Kedgwick River about 90 kilometres northeast of Edmundston, New Brunswick, was selected. The principal motive for the Fraser Timber Company's interest in using the area in an evaluation of GIS was its complexity. The site is complex for three main reasons. First, the topography of the area is steep, which has limited conventional logging practices. Second, the necessity of complying with a strict set of timber cutting regulations imposed by the New Brunswick Provincial government, which owns this section of the Kedgwick, has further limited logging of the site, rights to which are held by the Fraser Company alone. Third, the presence of a lodge on the site, which is owned by the Fraser Company and used by its executives and clients, has fostered an interest group that is resistant to any major change in the virgin forests of the Kedgwick area. Together, these situations make managing the Kedgwick area difficult.

Principal access to the site is via forest roads. Deer, the main wildlife management concern, have extended their northern range into the area. The New Brunswick Department of Natural Resources has designated special winter cover areas within the site as protected wintering deeryards. Overall, human beings have thus far had little influence on the study site.

The forests of the study site are predominantly spruce and fir (70 percent). Pine (mainly Red, Jack, and White) makes up another five percent of the area's softwoods; the remaining softwoods include larch, hemlock, and cedar. Hardwoods, which are found in the area in dominant patches, are a minor part of the overall vegetation (18 percent). An infestation of the sprucebudworm has affected ten percent of the trees on the site, killing many of them and thus contributing significantly to the area's fire fuel load. Much of the vegetation in the area is reaching the overmature stage, which also adds to the fire fuel load.

THE MAIN MODEL DESIGN

The first three steps involved in developing the main model were (1) definition of design objectives, (2) inventory of existing resources, and (3) creation of a data base. In defining the design objectives of his study, a manager is forced to decide how to approach the major management problems of a study site, a process of weeding out what he does not want to do with the landscape from what he wants to do. For example, extensive clear cutting might be discarded as a possibility for an area having high recreational potential. The manager must also determine all land-use options that the landscape might support (for example, canoeing, fishing, and wildlife preservation). Creation of the data base is guided by the manager's management objectives. Only information necessary to meet the objectives would be included in the data base.

The model uses the data base to analyze land suitability. It employs six submodels: visual quality, landscape ecology, potential natural vegetation, fire management, wind management, and production and economics. A suitability map is produced from each of the six submodels. The maps portray the priority weighting of each area in the study site according to the land management question being examined. For instance, if the landscape ecology submodel was being run, and management for deer was the design objective, the cells most critical to the deer population would receive the highest weightings and the cells of least value to deer would receive the lowest weightings on the output suitability map.

Minimum area thresholds are set at this stage (Hills, 1976; Hills, 1978). Satisfying the minimum area thresholds is crucial; otherwise, resources that do not meet an established threshold may be wasted. For instance, if a particular mammal species requires 50 hectares of habitat to survive, but the manager reserves only 35 hectares for that species, then the animal would perish and the manager would wasted the 35 indentified hectares.

Once the suitability maps have been created and the minimum area thresholds have been determined, a manager returns to his management objectives as the next step in constructing an integrated output map. The manager first ranks each of the six submodels, which represent individual land management objectives, in accordance with its relative importance to his overall design objectives. For example, the design objective for a study site might be to optimize the area according to landscape ecology principles, but the manager may also be interested in pro-

†A scenario is any one of the numerous possible management plans that a manager might wish to implement on a given study site.

duction and economics, visual quality, and, to a lesser extent, fire management. The manager would decide how much of the study site should be allocated for these land management objectives and would assign a percentage to each. If the manager decided to allocate 65 percent of the total study site to landscape ecology, he would then select the highest weighted cells from the landscape ecology suitability map for a value equal to 65 percent of the total area. These cells would be encoded in an output file. If 15 percent of the area were to be assigned to production and economics, then the cells with the highest value weightings on the production and economics suitability map would be selected and added to the output file.

On adding the two files to the output file, the manager would likely discover that certain cells have been assigned both the landscape ecology and the production and economics priorities. In most cases, the manager will want to resolve such a conflict by examining the overlap and then selecting one land management objective over the other. If the cells with overlapping management priorities received lower weightings on the landscape ecology suitability map than on the production and economics suitability map, the manager could assign the cells to the production and economics objective on the output map.

In order to make up for the landscape ecology cells lost to the production and economics objective, the manager would subsequently have to select enough cells from the next highest weightings on the landscape ecology suitability map to again equal 65 percent. These cells would then be added to the final output map file. However, if the overlap occurred in the most critical or most valuable areas of the landscape ecology suitability map, or interfered with the minimum area threshold level for a certain objective, the manager might decide to assign the cells on the output map to the landscape ecology objective. The manager would then have to select enough lower value weightings from the production and economics suitability map to equal 15 percent and add them to the output file.

Fifteen percent of the area might also be assigned by the manager to high visual quality in order to meet the design objectives. The manager would overlay the top 15 percent of the highest weighted cells from the visual quality suitability map onto the output map. Once again, potential conflicts would have to be examined. Should overlap occur between the visual quality and production and economics objectives (both of which have been allocated to 15 percent of the study area), then the objective having the higher weighting will probably dominate on the output map. Overlap between visual quality and landscape ecology suitability demands the same allocation procedures as used in the instance of the landscape ecology/production and economics overlap discussed above. Finally, these same procedures would be utilized in adding the top five percent of the fire management suitability map (the percent assigned by the manager to meet the objective) to the final output map.

At this point the manager would evaluate the final map*. If he so decided, the manager could then try a new management scenario, changing the percentage allocated to each submodel to meet the objectives of the new scenario. He would run the main model again to create a new final output map and then evaluate the product. The result could be compared with the result of the first scenario to determine which of the two scenarios best meets the design objectives. The strength of the GIS is fully revealed at this point, for the manager will be able to analyze immediately the ways in which the two management scenarios would influence the study site.

IMPLEMENTATION OF THE MODEL

The data base created for this study included topography, soils, glacial deposits, vegetation (immature spruce, mature spruce, overmature spruce, immature fir, mature fir, overmature fir, other spruce/fir, pine, other softwoods, hardwoods, dead softwoods), windthrow affected areas, spruce-budworm affected areas, forest crown closure, forest development stage, deeryards, water, and roads. All data were converted to raster format for analysis. The data base had a spatial resolution of 0.4 hectares.

Suitability maps were produced by running each submodel. Pertinent data from the data base were reduced by means of the six submodels to nine suitability maps (see Johnston, 1986). The suitability map produced by the visual quality submodel, for example, considered whether a cell could be seen from a river or road, its location in the cone of vision, its distance from the viewer, and the preference ratings of its attributes (for example, natural rock outcroppings usually received a higher preference rating than manmade detritus). A map of potential views with no obstruction by vegetation was also created by the visual quality submodel.

The landscape ecology submodel produced two output products. The first, which portrayed deeryards and corridors, was considered a minimum area threshold map; therefore, as noted earlier, it was inviolable in later decision making. The second output map assigned values to each cell of the study site in accordance with the principles of landscape ecology (Forman and Godron, 1986; Johnston, 1986). The most important cells received the highest weightings. A map of land suitability for optimum natural vegetation was contributed by the potential natural vegetation submodel. The wind management submodel produced a map that weighted each cell according to its susceptibility to windthrow.

The fire management submodel assigned weightings to each cell on the basis of three fire-related characteristics: (1) the likelihood of a fire originating in any given cell; (2) the likely intensity of a fire in any given cell based on site characteristics and fuel load; and (3) the relative rate at which a fire would spread through any given cell. When the three overlays representing these characteristics were added together, they produced a single fire hazard output map. Those cells in which a fire was most likely to originate and in which a fire, once ignited, would burn most intensely and spread most rapidly received the highest ratings. A map portraying timber areas divided into nine prioritized cutting zones was derived from the production and economics submodel. A cost-of-construction friction map†, for building roads, was also derived using the production and economics submodel.

A specific management scenario may be run through the main model in several ways. The most efficient way, the one used in this study, involves assigning percent weightings (zero to 100 percent) to each submodel (for example, visual quality) in accordance with the importance of that submodel's particular objective to the overall design objective. The more important a submodel output was to the design objective, the higher the percentage assigned. The percent value assigned to each submodel equaled the total percent of cells assigned to it on the final output map. By changing the weightings of the submodels, the manager could test different management scenarios quickly.

The first scenario tested on the Kedgwick study site set five design objectives, presented in order of importance: (1) logging, (2) preserving the most ecologically important areas, (3) preserving visual quality, (4) controlling fire, and (5) reducing windthrow. A weighting of 45 percent was assigned to the production and economics (or logging) objective; 35 percent to the landscape ecology objective; ten percent to the visual quality objective; and five percent each to the fire management and wind management objectives. The highest weighted cells on

*An automated technique for assisting in evaluation of the output maps is presented in Johnston (1986).

†The friction map had values assigned to each cell dependent upon costs of construction (based on site characteristics) and the benefits (the amount of timber) to be gained from building a road.

each individual suitability map were selected for placement on the final output map in the manner described previously. Before placing the highest weighted cells from each suitability map on the final output map, a unique number was assigned for tracking purposes. For example, "7" was assigned to the most critical* 7,963 cells of the landscape ecology suitability map (35 percent of the study site); and "11" was assigned to the most critical 1,138 cells of the fire management suitability map (five percent of the study site). The prioritized and recoded overlays were then added together to produce the final output map.

As expected, examination of the final output map showed that many cells had two or more potential management uses assigned to them. In order to determine for each multi-use cell a single-use management objective, a matrix was prepared as a reference to all possible combinations of the unique values assigned to each cell. Using the matrix, the manager could then examine the overlap before determining the best management use. Consider, for example, that a cell received high values on the visual quality, production and economics, and landscape ecology suitability maps, and had been assigned all three objectives on the final output map. The manager would have to specify a single final management use for the cell. After reviewing the original design objectives for the scenario, the manager would note that the production and economics objective was given higher value than the landscape ecology and visual quality objectives. Therefore, he would assign the cell in question to the production and economics objective on the final output map.

After all cells from each of the recoded suitability maps were assigned to the output file, the manager could observe on the final map the number of cells assigned to each objective to determine how closely the allocation came to the number of cells designated in the design objective. Only 4,789 cells (20 percent) of the study area were assigned to the landscape ecology objective during the first round of implementing the model on the Kedgwick study site. However, 7,963 cells were needed to meet the 35 percent objective. Consequently, an additional 3,084 cells had to be assigned to that objective. The manager selected the next 15 percent of the cells rated highest on the landscape ecology submodel output map. This process was continued for the production and economics, visual quality, fire management, and wind management objectives. Cells reassigned during this second round were recoded to the appropriate unique number established earlier for each objective, and then added to the final output map. Conflicts were again prioritized and assigned to the output map according to the logic cited above. This entire process was repeated until the appropriate number of cells for each objective had been achieved on the final output map. The results of applying this methodology to the second scenario of the many management scenarios that were run is shown in Figure 2.

Once all cells in the study had been assigned management objectives, those cells to be designated for cutting were identified. Site entry and exit points closest to the areas to be logged also were noted. The priority weightings obtained from the production and economics suitability map were added to the road friction map (developed during an earlier stage of analysis) to insure that a proposed road would pass through the areas to be cut. The friction map was used to compute a route to the desired points of entry and exit that would be least expensive to construct.

DISCUSSION

A major problem was encountered in adding together all of the recoded intermediate maps produced for each round. It was difficult, especially during the later rounds of the process, to determine the way in which decisions regarding conflict had been resolved. For example, during the third round, all recoded maps were added together and then added to the final output map. In this final map, it was difficult to determine whether a cell, which may have had conflicting assignments from the visual quality, landscape ecology, and production and economics land uses, had been assigned its final management use by having the top priority in round one or the least priority in round three.

*Critical cells were those cells with the highest values on the suitability map.

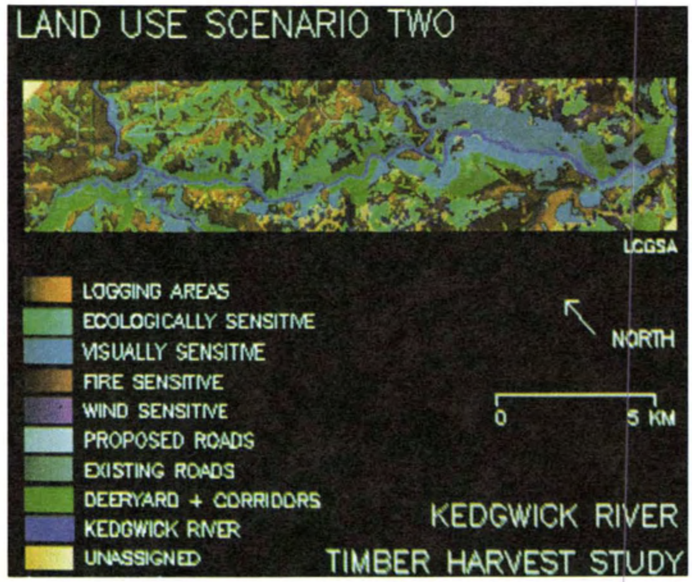

FIG. 2. Land-use map for Scenario Two of study. Design objectives for this scenario were 30 percent for production and economics, 30 percent for landscape ecology, 20 percent for visual quality, 15 percent for fire management, and 5 percent for wind management.

Close examination revealed that this factor had, indeed, caused error. Recall that unique numbers had been assigned to each cell in the intermediate map (for example, "7" to cells assigned to landscape ecology). Because all of the maps from one round had been added together, the manager, in following his design objective, inadvertently assigned some cells to the wrong objectives. To correct the error, the manager separately added each individual objective map to the final output map and resolved conflicts before adding the next objective map. This procedure allowed for backtracking easily to the original suitability maps where cells with conflicting assignments could be examined and their weightings in the original suitability maps identified.

CONCLUSION

Although creation of the data base and submodel suitability maps involved considerable time, once the suitability maps had been produced, the main model made rapid examination of numerous management scenarios possible. This enabled the manager to review and test a large number of alternative design objectives before selecting the best objective for the study site. The model should, however, be tested in other landscapes and environments. Artificial intelligence (AI) techniques should be of assistance in handling decisions regarding the assignment of a single management objective to a cell with conflicting objectives or the comparison of scenarios.

ACKNOWLEDGMENTS

This project was supported by the Harvard Laboratory for Computer Graphics and the Harvard Graduate School of Design. The author would like to thank Denis White and Jonathan Corson-Rikert of the Graphics Lab; Dana Tomlin, Richard Forman, Bruce Milne, and Carl Steinitz of the Design School; Ernest Gould and David Foster of the Harvard Forest; and Jerry Franklin of the United States Forest Service for their input. The author is also grateful to the Fraser Timber Company for providing a study site, data, and technical support. Martin Litchfield, Randy Webb, and Chris Bowers of Fraser were highly instrumental to this study.

REFERENCES

Brockman, C.F., and L.C. Merriam, Jr., 1973. *Recreational Use of Wild Lands*, 2nd ed., McGraw-Hill, New York.

Bureau of Land Management, 1980. *Visual Resource Management Program*, Washington, D.C. Stock No. 024-011-00116-6.

Forman, R.T.T., and M. Godron, 1986. *Landscape Ecology*, John Wiley & Sons, New York.

Hills, G. Angus, 1976. An Integrated Interative Holistic Approach to Ecosystem Classification. *Proceedings First Meeting Canadian Commission on Ecological (Biophysical) Land Classification*, Petawawa, Ontario, Canada, May 25–28, 1976.

———, 1978. "An Ecosystem Framework for Landscape Evaluation." Canadian Society of Landscape Architects, Winnipeg, Manitoba, Canada, 12 August 1978.

Johnston, Kevin M., 1986. *Natural Resource Modeling in the Geographic Information System Environment*. Department of Landscape Architecture, Harvard University, Cambridge, Mass.

McHarg, Ian L., 1971. *Design with Nature*, Doubleday & Co., Doubleday/Natural History Press, Garden City, New York.

USDA Forest Service, 1974. Chapter 1, The Visual Management System, *National Forest Landscape Management*, Vol. 2, Washington, D.C. Handbook No. 462.

———, 1977. Chapter 5, "Timber," *National Forest Landscape Management*, Vol. 2, Washington, D.C. Handbook No. 559.

New Sustaining Member

Science Applications International Corporation
Advanced Applications Operation
803 W. Broad Street, Suite 500, Falls Church, VA 22046
Telephone: (703) 241-7900

The Advanced Applications Operation (AAO), of Falls Church, Virginia, with 130 professional and support staff, is part of the Science Applications International Corporation's (SAIC) nearly 7,000 employees and $540 million annual revenue. SAIC is a diversified high-technology company focusing principally in the areas of national security, energy, environmental protection and health. Organized in 1969, SAIC has evolved from a small cadre of research scientists into a broadly based scientific and technical problem solver, capable not only of devising innovative solutions but also applying those solutions to key national problems.

SAIC/AAO contains two divisions located at 803 West Broad Street in Falls Church, Virginia, with a third division located in Melbourne, Florida. AAO contains an extensive variety of technical disciplines including photogrammetrists, geodesists, engineers, physicists, mathematicians and computer scientists. This selected group of professionals have dedicated computer processing support, high resolution image processing systems, and access to a supercomputer.

AAO has conducted a number of projects concerning MC&G, photogrammetry and image sensing. Specifically:

- Cartographic applications of Synthetic Aperture Radar. Imagery is displayed on a digital imagery display screen in mono and stereo. Both optical and SAR can be displayed simultaneously for synergistic studies. Full mensuration capabilities are also provided.
- CRAY supercomputers to support high speed imagery processing. Various architectures have been assessed, and studies are being conducted to investigate the use of knowledge–based systems to enhance supercomputer cartographic applications.
- Automated cartography. A demonstration system has been developed to integrate image processing, pattern recognition and artificial intelligence into automated cartography. An extensive knowledge–based system is under development to automatically extract features. Several computer vision tools are also provided to assist in the automatic delineation of features.
- Image processing and pattern recognition. A scheme for automatic texture classification to segment features of interest and to classify the segmented features, has been developed. Computer vision primitives are used to establish initial image segmentations. The segmentations are identified, attributed and edited using knowledge–based techniques.