Micheál L. O'Brien
Patrick A. Miller
Lee R. Skabelund
Claudia G. Phillips

Visualization in Decision-Support Systems:

A Proposal for the New River Gorge National River

Introduction

The New River Gorge National River (NRGNR) faces a problem common to most protected areas: its integrity is dependent on the mutual understanding and collaboration of multiple stake-holders within and around the area. Collaborative decision-making has been declared essential to realizing sustainable ecosystem management. In addition to requiring innovation in physical techniques, ecosystem management requires innovation in the human dimensions of protected areas management. Learning and communication are the basis of that collaboration. People must have a shared understanding and be able to communicate clearly about the resources and issues in order to make decisions and reach agreement. Information systems that aid solving complex problems by augmenting the user's knowledge are called *decision-support systems* (DSS's). Supporting learning and communication are basic functions of a DSS. Visualization can be applied to meet these learning and communication needs. Visualization is the use of representations to aid visual thinking and visual communication, a mode that is particularly suitable for ecosystem information. Maps, images, diagrams and graphs are typical representations used to aid thinking about an ecosystem. This paper presents a concept for a DSS for the NRGNR, and suggests visualization applications for the proposed Land Management System of the New River Parkway. The paper concludes with a brief discussion of the problems and potentials of implementing such a system.

Decision-making Needs In Ecosystem Management

Case of the New River Gorge National River

The New River Gorge National River of West Virginia provides a rich mix of natural and cultural resources, as well as recreational attractions. The integrity of these resources depends on the cooperation of many stake-holders. The National River is located in the lower reaches of the New River Basin amidst a complex pattern of ecosystems, land uses, and ownership. The New River passes through two mountain chains, three states, and several counties before cutting into the Allegheny Plateau to form the gorge below the town of Hinton. River flows up to this point are regulated by two major dams, one managed by an electrical utility, and the second, just above Hinton, by the Army Corps of Engineers. Wetlands, fish, and wildlife are regulated by both federal and state agencies. The water quality of the river is largely determined by land uses in the river basin, which are minimally regulated by various local governments of three states. Development in the gateway communities around the National River occurs without the guidance of land-use regulations. To protect those resources occurring on the private land, the U.S. National Park Service (USNPS) relies on monitoring of resources and cooperative agreements on management, and also provides technical assistance on management (USNPS 1982). The proposed New River Parkway would implement a Land Management System, administered by the local governments, to guide land use on the private land within the parkway corridor. For National River lands managers must ultimately rely on the cooperation of the users to avoid conflicts and mitigate recreational impacts. Communication and interpretation are typical methods of managing user behavior. For this protected area, as in most, users, neighboring land owners, managers, and officials are all actors in resource decision-making.

The Context of Ecosystem Management

The problems facing the NRGNR are examples of problems basic to sustainable ecosystem management. The ecosystem approach has been proposed as a new paradigm in environmental management for protected and multiple-use natural areas (Agee and Johnson 1988), and even human settlements (Lyle 1985). Increasing appropriation of natural resources and evidence of global environmental change has raised concerns about the sustainability of trends in natural resource use. The goal of ecosystem management is to maintain the health of the ecosystem while providing for sustainable human use. Current scientific thought suggests that ecosystems are more complex, dynamic, interrelated, and extensive than we have been managing for; this implies the need for major innovations in natural resource management (Slocombe 1993). Ecosystem approaches stress the need for the integrated management of multiple resources over larger areas and longer time frames than presently attempted. The complexity of such management exceeds the capacity of current science to propose management strategies with predictable results, suggesting that an adaptive experimental management approach is called for (Kessler et al. 1992).

The question for environmental scientists is how to expand interdisciplinary collaboration to build a more comprehensive science. For public agencies, the scale of ecosystem management implies the need to coordinate their activities to effectively manage shared resources (Agee and Johnson 1988). Public support for such extensive management, which may also include private lands, must be developed through more participatory planning processes (Slocombe 1993). These contemporary issues of ecosystem management are in many ways simply expansions of perennial issues in protected areas management. To preserve the natural heritage of a place and to build societal appreciation and support for that heritage is central to the mission of U.S. national parks.

Learning and Communication Needs in Ecosystem Management

For this discussion we will consider ecosystem management as consisting of two major processes: the *technical* and the *social*. The technical process involves the science and method of analyzing and manipulating the physical components of the ecosystem. The social process involves the steps in decision-making that guide implementation of the technology. Social processes include promoting public awareness, developing consensus on policy goals and management actions, and cooperating in implementation. In this paper we focus on two basic human processes fundamental to decision-making—learning and communication.

The complexity of ecosystems and the increasing complexity of their management suggest that society ought to learn more about ecosystems. Learning can be defined simply as the assimilation of information within a person. Two characteristics of ecosystems relevant to learning are *complexity* and *interrelatedness*. Complexity results from the multi-dimensional and dynamic nature of ecosystems. The implication of complexity is the difficulty of comprehension and the uncertainty of analysis and prediction. Interrelatedness of ecosystem components and processes call for holistic approaches to understanding ecosystems. The following are some general ecosystem learning needs:

- To increase knowledge of ecosystems and their management across society in order to develop societal appreciation and support.
- To increase understanding among the scientific disciplines in order to develop integrative concepts and methods for management.
- To increase understanding among the scientists and the managers in order to develop effective and practical methods.
- To increase understanding among stake-holders—all interested parties—in order to develop appreciation of each other's interests and find areas of agreement.

Both the Park Service and its advocates have noted the importance of the educational role for the agency. The USNPS has stated the importance of education and communication outreach to building supportive constituencies and partnerships for resource protection (USNPS 1992). Further, it has been suggested that the educational role of national parks be strengthened to develop public understanding and motivation to deal with large-scale environmental problems (NPCA 1989).

Learning about ecosystems requires the ability to communicate about them. Additionally, to collaborate in ecosystem management, citizens, managers, and scientists need to be able to communicate clearly with each other. Communication can be defined simply as the transfer of information among people. The complexity of ecosystems makes communication challenging, particularly across differences of expertise. The novelty of ecosystem management also increases the difficulty of communication. It is difficult to talk about things that are not yet part of a shared experience and language. The following are some general ecosystem communication needs:

- Scientists and managers must be able to communicate with each other about research findings and needs, as well as about the newly discovered values of the resources and innovations in management.
- Scientists must be able to communicate with each other across domains of knowledge.
- Managers must be able to communicate with each other across resource specializations and among agencies.
- Citizens must able to communicate with managers and other stake-holders about their values for the resources.

As with learning, the public agencies have a central role in facilitating the communication among stakeholders in ecosystem management. In the following discussion we will outline characteristics of an information system that addresses ecosystem learning and communication.

Decision-Support Systems

The technical and social processes of ecosystem management involve different types of decision-making, which in turn benefit from different types of support from information systems. Technical decisions, such as those which occur in operational management, have agreed-upon objectives, and tend to be quantifiable, predictable, and have established solutions. These types of decisions are amenable to analytical computing to find optimum solutions. Social decisions, such as those which occur in policy development and management planning, typically include technical issues (though often in interrelated sets), but center on subjective issues such as goals and evaluation. Social decisions cannot be automated, and they ultimately require the exercise of human judgment. Also, in ecosystem management technical decisions may have high degrees of complexity and uncertainty, and so even technical management decisions may require some judgment.

DSS's are a class of information systems designed to help solve complex and poorly structured problems by augmenting human judgment. A

DSS will typically provide a set of tools that will support the process of problem structuring, understanding the problem, producing alternative solutions, and evaluating them (Guariso and Werthner 1989). To serve a broad range of users, DSS's must facilitate understanding of the analysis and the understanding and interpretation of its results (Langendorf 1985). DSS's have also been developed to facilitate group processes in decision-making (Bishop 1993). The advancement of DSS's in natural resource management is a necessary complement to traditional emphases on quantitative computing.

Within these general functional definitions, such systems can be diverse in specification, integrating hardware and software from various types of systems. Components of a DSS in environmental management can include: hypermedia databases, geographic information systems (GIS's), image processing, systems models, expert systems, intelligent and graphical user interfaces, and document handling. A hypermedia database combines information in multiple media (numbers, text, images, and sound) in an associative framework that links related information, facilitating knowledge building. Expert systems provide the foundation of decision-support by applying formalized expert knowledge to assist users in problem analysis and solution. Intelligence is also being built into the interfaces of systems to provide on-line assistance in the use of the system. Graphical user interfaces have become standard for displaying information in easily read displays of maps, graphs, diagrams, and images. Document handling allows system products to be disseminated beyond direct interaction with the system. The GIS, for mapping and analyzing spatial data, has become standard in environmental management, as most natural resources have a spatial dimension, and are a component of most environmental DSS's. Image processing is used both for the interpretation of satellite imagery and for the editing of viewshed images to simulate visual changes. Systems models are mathematical models of natural processes used to describe and predict resource dynamics and impacts.

Systems falling into this category are an area of rapid development in environmental management. Two systems under development for multiple-use lands are the TEAMS system (Covington et al. 1988) and the IRMA system (Loh et al. 1992). These integrate resource output models with spatial data, use expert assistance in the interface to guide the user, and provide graphical displays to allow visual inspection of data and model outputs. Examples of integrated systems for protected areas are systems for the Channel Islands National Park (Reynales 1990) and Redwood National Park (Rogers 1990). These systems integrate database management with GIS capabilities and record expert resource knowledge to support the protection of natural and cultural resources for those sites. Broad utilization of GIS has been limited by the expertise required to operate the systems; intelligence in GIS systems can be used to aid users with unfamiliar phenomena, models, and systems (Coulson et al. 1991). Similarly, expert systems are being developed to assist non-specialist managers with visual resource assessments (Buhyoff et al. 1994). Graphical user interfaces have been applied in developing a user-friendly information system to transfer research findings to managers (Reyes et. al. 1993). Hypermedia systems have been proposed as a format to integrate, store, and make accessible large bodies of knowledge, such as that relating to global climate change (Rauscher et al. 1993). Most of these systems apply visualization in various forms—maps, images, diagrams, and graphs—to more effectively communicate environmental information and enhance understanding. System developers generally proclaim, and take for granted, the power of visualization. The next section describes the capabilities of visualization and why it is particularly suited for environmental information.

Environmental Visualization

We define visualization generally as the use of visual representations to aid visual cognition and visual communication. Visual cognition is regarded as one of the more powerful capacities of the mind, and visual representations have the ability to represent large amounts of information. Visualization has a long history of use in the arts (Arnheim 1964), design (McKim 1972), geography (MacEachren et al. 1992), and science (Ferguson 1977). Advances in graphical computing have stimulated current development in scientific visualization (McCormick et al. 1987) and environmental visualization (Orland 1992). Information technology has greatly increased our ability to capture and create images, thus increasing support for visual thinking and communication.

Visual Cognition and Cognitive Landscapes

Visual cognition can be defined to include the perception, processing, and storage of visual information. Visual cognition is characterized as being direct, holistic, and memorable (Haber and Wilkinson 1982). Visual information is encoded directly, without translation into other mental representations (like words or numbers), allowing quick processing. Visual patterns are perceived holistically; all elements and their visible relationships are recognized simultaneously, and even subtle or complex patterns are discernible. Retention of visual information is higher than for words or numbers, with the long-term memory of visual information apparently unlimited. An irony of visual cognition is that it is so pervasive and facile that it is not apparent to us how much we employ it (Kaplan and Kaplan 1982). The power of visual cognition suggests that it has inherent capabilities to deal with the quantity and complexity of ecosystem information.

Visual cognition, beyond having the power to handle the complexity of ecosystem information, may be particularly structured for understanding ecosystems. Evolutionary theory would suggest that natural selection favors those humans better adapted to understanding their environment. Environmental psychologists think that humans construct a mental model of the landscape (ecosystem) through their interaction with the environment (Kaplan 1973). Visual perception is the primary source of information for this mental landscape model (Kaplan and Kaplan 1982). The majority of research on these models has focused on how they function as *cognitive maps*, representing space, location, direction, and scale in the environment (e.g., Downs and Stea 1977). But, in addition to spatial structure, it is apparent that the mental model must also represent the function of the system; the model is used to explain and predict how the environment works (Kaplan 1973). Moreover, the mental model includes subjective evaluations that humans associate with environmental features. Landscapes can have utilitarian resource values, experiential aesthetic values, and symbolic social values. In light of the multi-dimensional nature of the mental model, which is reflective of the system that it attempts to represent, it may be more appropriate to refer to the mental model as a *cognitive landscape*. The cognitive landscape is the source of understanding and the basis of acting in the environment, making it the foundation for environmental decision-making (Kaplan and Kaplan 1982). The cognitive landscape is largely constructed through visual perception of the landscape, and it can be visually imagined. It follows that visual representations of the landscape can facilitate clear communication and be readily assimilated into the mental model.

Visual Representations

Visual representations, or *visualizations*, are artifacts made to facilitate visual thinking and visual communication (after McKim 1977; MacEachren et al. 1992). Common examples in environmental management are the use of maps to show the spatial distribution of resources, and the use of graphs to show quantities of resources and their attributes. Visualizations act as external representations of mental imagery and function to extend the working memory of the brain, allowing us to think about larger and more complex problems than we can unaided (Norman 1993).

Visualizations may range from realistic, as in the case of video movies, to abstract, as in the case of data graphs. *Realism* tends toward representing the complete set of attributes of the real object, and the representation tends to have the same form as the real object (that is, tends to be isomorphic). *Abstraction* tends toward representing a reduced set of attributes of the real object, and the representation's form may have no similarity to that of the object. Realistic representations have the quality of *concreteness*; being perceived as closer to the actual direct experience of a real object, versus being abstract and indirect. As abstractness increases, the viewer must rely increasingly on prior knowledge to recognize the representation. As realism increases, the representation comes closer to being an experiential analogue. The concreteness of visualizations can promote clarity in understanding and communication over the use of language, which can be ambiguous and prone to stereotyping (Kaplan and Kaplan 1982). Abstraction does have the function of focusing attention to specific attributes of a object, and is part of the process of analysis and building concepts about things (Muerchke 1981).

A fundamental distinction between visualizations is whether the representation is of things that can be seen—*perceptual*; or is a visual representation of invisible objects or abstractions and concepts about things —*conceptual* (McKechnie 1976). Visualizations are intrinsically useful for representing physical phenomena (such as landscapes) because they have a spatial form by which they are visibly perceived, and which can be represented similarly in depicted form. Invisible physical phenomena, such as nutrient cycling, can be visualized conceptually by representing its spatial form and movement visibly in a diagram. Ecologists use diagrams of food webs, nutrient cycles, and hydrology for communicating landscape processes. Even non-physical things, such as knowledge domains, can be represented visually, making them easier to conceptualize through spatial metaphor. Visible objects can also act as symbols of associated concepts, such as the use of landmarks and artifacts in historical interpretation to make history more concrete.

Utility of Visualization in Ecosystem Management

We suggest that visualization has a necessary role in decision-making for ecosystem management. Consider the following points that summarize and build on the preceding discussion. First, the concept of cognitive landscapes suggests that humans are innately predisposed to learning about landscapes, with visual cognition as the dominant mode. Second, the ability to recognize patterns in visual information suggests an increased capacity to perceive complex phenomena, if represented visually. Third, visualizations allow humans to analyze and transform more complex objects than they can without external representations. Fourth, the strong memory for visual information can aid retention of learning (Rieber 1994). Fifth, the concrete, object-oriented quality of visualizations should bolster communication across language differences and across different areas of experience and specialization (Kaplan and Kaplan 1982). Sixth, evidence suggests that visualization should enhance the ability to generate innovations; visual thinking is known to be linked to creative thinking in the brain (Sperry

1973), and has been demonstrated to improve creative problem-solving (Antonietti 1991). Here are some examples of types of visualizations and how they have been applied in environmental management.

Visual simulations. Visual simulations are perceptual visualizations, primarily used by landscape architects, for realistically modeling visible changes in built and landscape features (Sheppard 1989). Visual simulation has been used to model encroachment on viewsheds of historic sites, such as Manassas National Battlefield, and to depict the character of development schemes in Yosemite National Park (Adams 1990). These models provide objective representations of visual change that permit each individual to personally evaluate change in visual quality and facilitate collaboration in planning and design.

Data graphics. Data graphics are conceptual visualizations, primarily used to aid statistical exploration and analysis (Tukey 1977). The basic example of this type is the two-variable graph, such as the runoff hydrograph that shows stream flow over time. *Scientific visualizations* are primarily of this type. Animated graphical displays of multivariate and dynamic systems allow scientists to see patterns in data that they could not before (see Earnshaw and Wiseman 1992). Such visualizations can also be useful in the communication of scientific knowledge to managers and users. Graphs and charts have been used in forest management software to facilitate comparison of resource outputs under varying management alternatives (Covington et al. 1988). Thematic maps, such as produced by GIS, can be data visualizations.

Multimedia maps. Maps vary from realistic, as in aerial photographs, to abstract, as in thematic maps, and though typically 2-dimensional plan views, they can also be cross-sections or other representations of earth systems (Muehrcke 1980). The use of GIS technology allows the digital representation of maps, and multimedia technology allows the integration of images, sounds, and text with the digital map. Hamilton and Flaxman (1992) are developing a spatialized multimedia database on the biological diversity of a natural area in the Sierra Nevada of California.

Graphical User Interfaces. Information systems are increasingly using graphical displays to represent the system to the user. These displays provide access to the functions of the system and enhance communication of information output by the system. In large databases, visual maps of the information are important to comprehension and navigation of the database. Icons are often used in place of words to represent programs and commands compactly and legibly. The interface may even be represented as a visual-spatial environment, as in the desktop metaphor of the Apple computer's operating system.

Place images. Place images are perceptual visualizations of real sites that show the pattern of major elements in one view. These models are typically aerial oblique perspectives and may be combined with reference maps and ground-level perspectives. Such models facilitate the conceptualization of the overall structure of a landscape. This model has been used in urban and landscape planning for communicating alternative development scenarios. A recent notable example is its extensive use in the landscape planning manual, *Dealing with Change in the Connecticut River Valley: A Design Manual for Conservation and Development* (Yaro et. al. 1989). From these representations people can also interpret various qualities, such as settlement density, habitat patterns, visual character, and social interaction.

Explained Images. Words can added to an image to explain its object: language adds conceptual content to a visualization. The simplest form of such a representation is a captioned picture. More powerful computerized examples include hypermedia databases that embed information links within pictures, or expert systems that interact with a user to analyze images. An example of such an expert system developed for visual resource management is the Explanation of Visual Assessments (EVA) system developed by Buhyoff et al. (1994).

Impact matrices. Impact matrices are conceptual visualizations that show interactions of resources and management, and the resulting impacts on ecosystem structure and function. The formatting of the information in a matrix allows a holistic comparison of impacts across the components of a system. This type of visualization is commonly used in environmental impact assessment.

Semi-formal models. Semi-formal models combine perceptual and conceptual visualizations to represent both the structural and functional dimensions of human ecosystems for planning and design (Lyle 1991). They are particularly useful for aiding conceptual comprehension, communication, participation, and alternative generation. A typical model of this type is a diagrammatic three-dimensional graphic of a landscape and its significant processes. A relevant example is a water budget model for a lake for dry and wet seasons of a year. The approximate volume of water flows is represented in the size of flow arrows and storage blocks, facilitating the comparison of water volumes from the various inputs (Lyle 1991). Such a model provides at once both the conceptual model for shared understanding and an artifact on which to base communications about the system.

A Decision-Support System for NRGNR

We now return to the case of the NRGNR and its need to promote collaborative management. The following proposal is a concept for an information system that would support a broad range of research, management, and recreational users in the NRGNR. These ideas arise from our shared experience in planning for the

New River Parkway (Williams and Skabelund 1995) and in developing environmental information systems, including the development of an expert system for visual resource management (Buhyoff et al. 1994), the development of a multimedia database and tutorial for barrier-free recreational design (Bork et al., in press), and the design of a hypermedia database for a natural area (O'Brien 1995). This proposal is voluntary on our part and in no way the responsibility of the National Park Service.

A fully developed DSS would, ultimately, include a hypermedia database, a GIS, image processing, systems modeling, expert systems, an intelligent graphical interface, and document handling as described earlier. But developing such a system would require a substantial funding commitment, a team of specialized personnel, and extensive data sources. This is a worthy long-term goal, but in the short term there is an initial intermediate approach that could still produce a broadly useful, yet economical, system. The first step would be to begin construction of the hypermedia database with stand-alone GIS and image processing systems. The database would be simply a descriptive compilation of the available information on the landscape, its management, and its stake-holders. This compilation would provide the foundation for the later construction of a more sophisticated formal DSS. The GIS and image-processing systems would provide the necessary spatial data-handling and visualization capabilities. These systems would not require as much expertise for information input as would more sophisticated and complex systems, and the use of existing stand-alone software would minimize investment in software development. Most of the NRGNR's learning and communication needs could be supported through this combination of systems. Basic functions of the system would be to provide a research compilation, a management record, a resource inventory, and a source of media and content for interpretive programming and public communication. Expert systems, systems models, integrated shells, and other sophisticated expansions could be developed later as needed and funded.

Visualization for the Land Management System

An important application of this system would be to provide visualization services as a technical outreach to aid local governments plan compatible developments in the gateway communities of the National River. The Land Management System proposed for the New River Parkway currently under study (USDOT and WVDOH 1994) is a fitting example. The Land Management System is a set of land-use regulations and design guidelines intended to protect water, vegetative, and visual resources in the corridor of the New River Parkway (Williams and Skabelund 1995). Local governments would be responsible for administering the system on private lands in the corridor, under the review and advisement of the New River Parkway Authority, on which the USNPS has a non-voting member.

There is little tradition of land-use regulation in the region, and public appreciation and support for it must be developed. To aid implementation of the Land Management System, some basic learning needs must be addressed. First, land development is an interaction of processes occurring incrementally over an extended period of time, and people typically do not anticipate the results of cumulative change. Second, the alternative development patterns implied in the Land Management System guidelines are novel to most of the decision-makers, so they will have difficulty understanding and evaluating them. Visualization provides the best medium for representing concretely these interacting dynamics and novelty, to support understanding of environmental change, and engage collaboration in guiding change.

Visualizations have been specified in the preliminary concepts of the Land Management System. Maps would be prepared of the *Scenic Corridor Site Plan* that identify management zones, and graphic examples of the design guidelines and performance standards would be used in the *Planning and Design Handbook.* Additional visualizations that would also be applicable are place images, visual simulations, and semi-formal models. Place images would provide an overview of the density and character of alternative development scenarios for the corridor. Visual simulations would provide realistic representations of landscape changes that allow anticipation of its future character. Semi-formal models could be used to develop a conceptual understanding of hydrology and water quality issues related to the development impacts of storm water run-off and septic systems.

Planning and implementation based on concrete visual models of the proposed development scenarios would facilitate people's understanding of possible environmental changes and the relative costs and benefits of the various management responses. Used in a participatory social process, these visualizations may help to overcome stereotypical negative responses to regulation and the consequent lack of adoption, compliance, and enforcement. With a holistic representation of the possible landscape and its qualities, people might see that they prefer the environment achieved through collaboration. Without the aid of visualizations, agreement on what the problems are and what the preferred alternative is would be more difficult and may not be achieved at all, leaving current land-development trends unchanged. Similarly, if the consequences of greater environmental changes, such as climate change and extinction, are not made concrete and meaningful to peoples' experienced quality of life, it does not seem likely that alternatives will be considered.

Conclusions

Collaboration is required for achieving sustainable management of protected areas and other ecosystems, and collaboration is necessarily founded on shared understanding and clear communications. The continued development of DSS's can improve human judgment to guide the complex and contentious issues of ecosystem management. Human capabilities for visual cognition need to be utilized in the functions of an environmental DSS. Visualization will enhance understanding and communication across the range of stakeholders and should be a significant capability of the DSS.

The potential implementation of this proposal is not limited by technology, but by funding. Budgets for basic USNPS functions, not to mention developing information systems, have been inadequate. Increased funding for research has been advocated by scientific institutions (NRC 1992) and conservation organizations (NPCA 1989). The importance of protected areas to understanding and resolving larger environmental problems, like land degradation, climate change, and species extinction, reinforce the need for such an investment. However, current political trends offer little prospect for immediate funding. It is beyond the scope of this discussion to offer political strategies to resolve this problem. However, we have suggested that the communication functions of such a system could be applied to building public understanding and support for protected areas. This sets up the dilemma of which comes first—the support to develop the communications, or the communications to build the support. A near-term strategy of developing partnerships and combining resources with other institutions, such as regional colleges and universities, is one way for the NRGNR to begin constructing the type of information system proposed here.

References

Adams, C. 1990. Visual protection of national parks. Pp. 321-330 in *Resource Technology 90: Second International Symposium on Advanced Technology in Natural Resource Management,* G.J. Buhyoff, ed. Washington, D.C.: ASPRS.

Agee, J. K., and D. R. Johnson, eds. 1988. *Ecosystem Management for Parks and Wilderness.* Seattle: University of Washington Press.

Antonietti, A. 1991. Why does mental visualization facilitate problem-solving? Pp. 211-227 in *Mental Images in Human Cognition,* R.H. Logie and M. Denis, eds. New York: North Holland.

Arnheim, R. 1964. *Art and Visual Perception.* Berkeley: University of California Press.

Bishop, P. C. 1993. An introduction to Group Decision Support Systems. *The Environmental Professional* 15:156-158.

Bork, D.R., D.A. Mahon, and R. Parrish (in press). Teaching universal design with multimedia tutorials. Pp. 217-230 in *Strategies for Teaching Universal Design,* P. Welch, ed. Berkeley, California: MIG Communications.

Buhyoff, G.J., P.A. Miller, J.W. Roach, D. Zhou, and L.G. Fuller. 1994. An AI methodology for landscape visual assessments. *AI Applications in Natural Resource Management* 8:1-13.

Coulson, R. N., C.N. Lovelady, R.O. Flamm, S.L. Spradling, and M.C. Saunders. 1991. Intelligent geographic information systems for natural resource management. Pp. 153-172 in Quantitative Methods in Landscape Ecology, in M.G. Turner and R.H. Gardner, eds. New York: Springer-Verlag.

Covington, W.W., D.B. Wood, D.L. Young, D.P. Dykstra, and L.D. Garre. 1988. TEAMS: a decision support system for multi-resource forest management. *Journal of Forestry* 86(8): 25-33.

Downs, R. M., and D. Stea. 1977. *Maps in Minds: Reflections on Cognitive Mapping.* New York: Harper & Row.

Earnshaw, R.A. and N. Wiseman. 1992. *An Introductory Guide to Scientific Visualization.* Berlin: Springer-Verlag.

Ferguson, E. S. 1977. The mind's eye: nonverbal thought in technology. *Science* 197:827-836.

Guariso, G., and H. Werthner. 1989. *Environmental Decision Support Systems.* New York: Halsted.

Haber, R.N., and L. Wilkinson. 1982. Perceptual components of computer displays. *IEEE Computer Graphics and Applications* 24(5):23-35.

Hamilton, M. P., and M. Flaxman. 1992. Scientific data visualization and biological diversity: new tools for spatializing multimedia observations of species and ecosystems. *Landscape and Urban Planning* 21:285-288.

Kaplan, S. 1973. Cognitive maps in perception and thought. Pp. 63-78 in *Image and Environment: Cognitive Mapping and Spatial Behavior,* R.M. Downs and D. Stea, eds. Chicago: Aldine.

Kaplan, S., and R. Kaplan. 1982. *Environment and Cognition: Functioning in an Uncertain World.* New York: Praeger.

Kessler, W. B., H. Salwasser, C.W. Cartwright Jr., and J.A. Caplan. 1992. New Perspectives for sustainable natural resources management. *Ecological Applications* 2:221-225.

Langendorf, R. 1985. Computers and decision-making. *American Planning Association Journal* 51: 422-433.

Loh, D. K., et al. 1992. Integrated resource management systems: Coupling expert systems with data-base management and geographic information systems. *Environmental Management* 16:167-177.

Lyle, J. T. 1985. *Design for Human Ecosystems: Landscape, Land Use, and Natural Resources.* New York: Van Nostrand Reinhold.

———. 1991. The utility of semi-formal models in ecological planning. *Landscape and Urban Planning* 21:47-60.

MacEachren, A. M., B.P. Buttenfield, J.B. Campbell, D.W. DiBiase, and M. Monmonier. 1992. Visualization. Pages 99-137 in *Geography's Inner World: Pervasive Themes in Contemporary American Geography,* R.F. Abler, M.G. Marcus and J.M. Olson, eds. New Brunswick, N.J.: Rutgers University Press.

McCormick, B. H., T.A. DeFanti, and M.D. Brown, eds. 1987. Special issue: Visualization in scientific computing. *ACM SIGGRAPH Computer Graphics* 21(6).

McKechnie, G. E. 1976. Simulation techniques in environmental psychology. Pp. 169-189 in *Psychological Perspectives in Environment and Behavior,* D. Stokols, ed. New York: Plenum Press.

McKim, R. H. 1972. *Experiences in Visual Thinking.* Monterey, California: Brooks/Cole.

Muehrcke, P. 1981. Maps in geography. Pp. 1-41 in *Maps in Modern Geography,* L. Guelke, ed. Cartographica.

NPCA [National Parks and Conservation Association]. 1989. *National Parks: From Vignettes to a Global View.* Washington, D.C.: NPCA.

NRC [National Research Council]. 1992. *Science and the National Parks.* Washington, D.C.: National Academy Press.

Norman, D.A. 1993. *Things That Make Us Smart.* Reading, MA, Addison-Wesley.

O'Brien, M.L. 1995. Designing Hypermedia Landscapes: Applying a Concept of Landscape Cognition. Masters Thesis, Landscape Architecture Department, Virginia Polytechnic Institute and State University, Blacksburg.

Orland, B., ed. 1992. Special Issue: Data visualization techniques in environmental management. *Landscape and Urban Planning* 21(4).

Rauscher, H.M., D.H. Alban, and D.W. Johnson. 1993. Managing the global climate change scientific knowledge base. *AI Applications in Natural Resource Management* 7(4):17-39.

Rieber, L.P. 1994. *Computers, Graphics, and Learning.* Madison, Wisconsin: WCB Brown and Benchmark.

Reyes, E., J.W. Day, Jr., M.L. White, and A. Yanez-Arancibia. 1993. Ecological and resource management information transfer for Laguna de Terminos, Mexico: a computerized interface. *Coastal Management* 21:37-51.

Reynales, T.E. 1990. An integrated data management system for ecological monitoring and resource management in Channel Islands National Park. Pp. 359-368 in *Resource Technology 90: Second International Symposium on Advanced Technology in Natural Resource Management,* G.J. Buhyoff, ed. Washington, D.C., ASPRS.

Rogers, J. A. 1990. Automated resource information system: a vision for the 90's. Pp. 387-395 in *Resource Technology 90: Second International Symposium on Advanced Technology in Natural Resource Management,* G.J. Buhyoff, ed. Washington, D.C., ASPRS.

Sheppard, S.R.J. 1989. *Visual Simulation: A User's Guide for Architects, Engineers, and Planners.* New York: Van Nostrand Reinhold.

Slocombe, D. S. 1993. Environmental planning, ecosystem science, and ecosystem approaches for integrating environment and development. *Environmental Management* 17:289-303.

Sperry, R.W. 1973. Lateral specialization of cerebral functions in the surgically separated hemispheres. Pp. 209-229 in *The Psychophysiology of Thinking,* F.J. McGuigan and R.A. Schoonover, eds. New York: Academic Press.

Tukey, J.W. 1977. *Exploratory Data Analysis.* Reading, Massachusetts: Addison-Wesley.

USDOT [United States Department of Transportation] and WVDOH [West Virginia Department of Highways]. 1994. New River Parkway, West Virginia: Pre-Draft Environmental Impact Statement. FHWA-WV-EIS-95-01-D.

USNPS [National Park Service]. 1982. *General Management Plan: New River Gorge National River, West Virginia.* Denver: Denver Service Center, USNPS.

———. 1992. *National Parks for the 21st Century: The Vail Agenda. Report and Recommendations to the Directory of the National Park Service.* Denver: USNPS.

Williams, L.T., and L.R. Skabelund. 1995. Bridging the gap between federal, state and local land management agencies: the New River Parkway Land Management System. Pp. 293-300 in *Sustainable Society and Protected Areas: Contributed Papers of the 8th Conference on Research and Resource Management in Parks and on Public Lands,* Robert M. Linn (ed.). Hancock, Michigan: The George Wright Society.

Yaro, R. D., R.G. Arendt, H.L. Dodson, and E.A. Brabec. 1989. *Dealing with Change in the Connecticut River Valley: A Design Manual for Conservation and Development.* Cambridge, Massachusetts: Lincoln Institute of Land Policy.

Micheál L. O'Brien, Patrick A. Miller, Lee R. Skabelund

Department of Landscape Architecture, 202 Architecture Annex, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0113

Claudia G. Phillips

Department of Environmental Design and Planning, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061